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CIRCUIT MODELS FOR INDUCTIVE STRIPS IN FIN-LINE

by

Georgios Karaminas

December 1989

Thesis Advisor Jeffrey. B. Knorr

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This thesis describes a C.A.D compatible circuit model for an inductive strip centered in WR(90) fin-line with W/b< 1, $E_r = 1$. The circuit model is shown to predict strip scattering coefficients which agree closely with those computed numerically using the spectral domain method.

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Circuit Models for Inductive Strips in Fin-Line

by

Georgios Karaminas
Lieutenant Hellenic Navy
B. S., Hellenic Naval Academy, 1979

Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN ELECTRICAL ENGINEERING

from the

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December 1989

ABSTRACT

This thesis describes a CAD-compatible circuit model for an inductive strip centered in WR(90) fin-line with $W/b < 1$, $E_r = 1$. The circuit model is shown to predict strip scattering coefficients which agree closely with those computed numerically using the spectral domain method.

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I. INTRODUCTION TO FIN-LINE

The use of fin-line as a transmission structure for millimeter- wave integrated circuits was first proposed by Meier in 1974 [Ref. 1]. The advantages of this structure are low-attenuation, single mode operation, containment of spurious emissions, ease of production, and compatibility with integrated circuit technology. Fin-line has become established as a viable transmission structure, and, therefore, studies contributing to its effective utilization are of widespread interest.

Knorr and Shayda have applied the spectral-domain method to determine the transmission characteristics of fin-line [Ref. 2: pp. 737-738] and Knorr [Ref. 3 pp. 1200-1201] has used the method to investigate the end effect in a shorted fin-line. Lastly, Knorr and Deal [Ref. 5, 6] have used the spectral domain method to compute the scattering coefficients of an inductive strip in fin-line. These studies addressed the proper choice of basis functions and accurately determined the fin-line guide wavelength and characteristic impedance as well as the equivalent reactance of a shorting septum, and the scattering coefficients of an inductive strip.

One discontinuity of considerable practical importance is the inductive strip in fin-line. It is used to construct simple resonators as well as more complicated multi-resonator filters. The geometry for a fin-line is illustrated in Figure 1 on page 2 and a cross-sectional view of the fin-line in which the strip resides is shown in Figure 2 on page 2. Figure 3 on page 3 shows cross-sectional views of three fin-line configurations [Ref. 4]. In the configuration of Figure 3b, the fins are printed on opposite sides of a single dielectric substrate. Since the fins are directly grounded to the metal waveguide walls, this configuration is applicable only to passive devices. In the configuration of Figure 3c, however, the fins are printed on the mating surfaces of the two dielectric substrates. Since the fins are insulated from the waveguide at dc, bias may be introduced for active components.

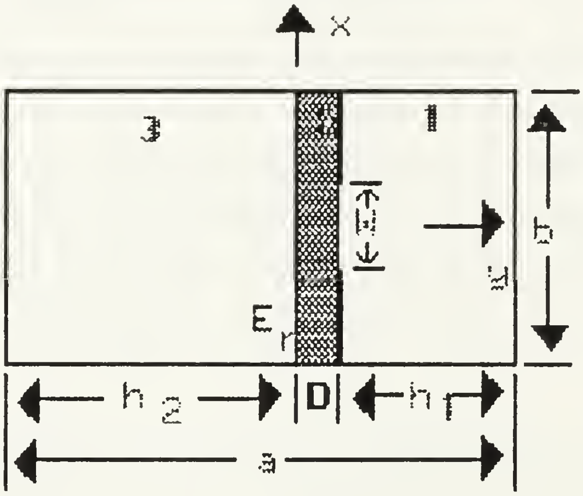


Figure 1. Cross-sectional view of a fin-line.

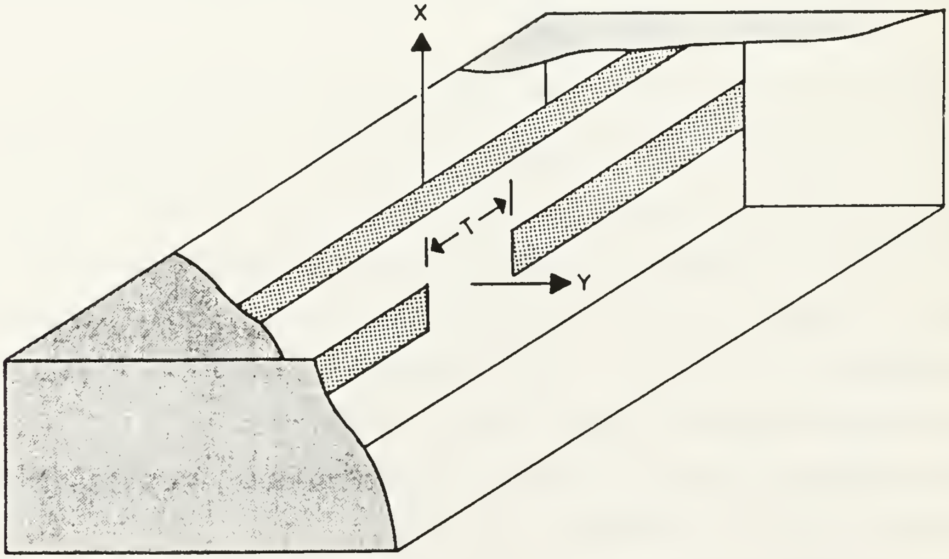
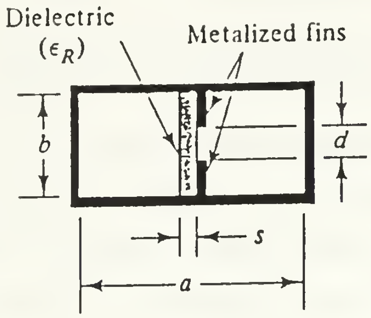
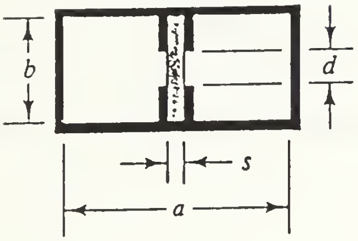


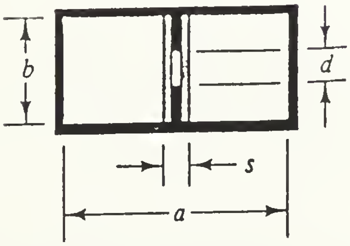
Figure 2. View of a fin-line strip of axial length T centered in a fin-line cavity.



(a) Unilateral



(b) Bilateral



(c) Insulated

Figure 3. Three typical fin-line structures.

The electric field in the plane containing the fins is predominantly in the x-direction. A wave incident on the strip induces a current on the strip and the associated stored magnetic energy of the evanescent field gives the strip its inductive property. If the strip is very long, the field decays with distance and the strip behaves like a shorting septum [Ref. 3: pp. 1196]. If the strip is sufficiently short, the incident wave is partially backscattered and partially forward scattered. The scattering coefficients S_{11} and S_{21} are functions of the strip width, fin separation, dielectric constant, shield size, and strip length.

The purpose of this thesis is to develop a circuit model for the inductive strip in homogeneous ($E_r = 1$) unilateral fin-line. The model will be developed by matching model data to numerical data derived from the spectral domain technique for different values of W/b and T/D.

This model can be used to design millimeter wave filters. Thus, a good check on the accuracy and utility of the model could be obtained by using the model to design some filters and then comparing the measured and predicted performance of the filters.

II. MODELING THE WR(90) FIN-LINE

The integrated fin-line structure can be viewed as a slotline with a shield, a ridged waveguide with dielectric, or a slab-loaded waveguide with fins. For thin slabs with low values of E_r, the fin-line structure is essentially the same as a narrow-width ridged waveguide. In practice, when fin-lines are constructed, the dielectric material is often allowed to pass through the broad wall of the shield [Ref. 2: pp. 737]. An additional dielectric spacer may be used to provide complete dc isolation of a fin from the shield. This allows biasing of solid-state devices mounted between the fins [Ref. 2: pp. 737]. The integrated fin-line is often utilized as a medium for constructing millimeter wave circuits. In this chapter we model the fin-line using spectral domain data, for wavelength and characteristic impedance.

For homogeneous fin-line the wavelength and characterictic impedance are given exactly by the relations 1(a):

$$\frac{\lambda'}{\lambda} = \frac{1}{\sqrt{1-(\frac{\lambda}{\lambda_c})^2}} \qquad Z_{0v} = \frac{Z_{0v\infty}}{\sqrt{1-(\frac{\lambda}{\lambda_c})^2}} \tag{1a}$$

$$Z_{0v} = (2\frac{b_{eq}}{a_{eq}})\eta_0(\frac{\lambda'}{\lambda}) \qquad \frac{\lambda'}{\lambda} = \frac{1}{\sqrt{1-(\frac{\lambda}{2a_{eq}})^2}} \tag{1b}$$

where λ_c and $Z_{0v\infty}$ are the cutoff wavelength and high-frequency limit impedance of the fin-line.

Figure 4 on page 6 shows a homogeneous fin-line structure as well as an equivalent rectangular waveguide structure. Since the homogeneous rectangular waveguide is governed by the same equations 1(a) for the cutoff wavelength and characteristic impedance, we can construct a waveguide with dimensions a_{eq} and

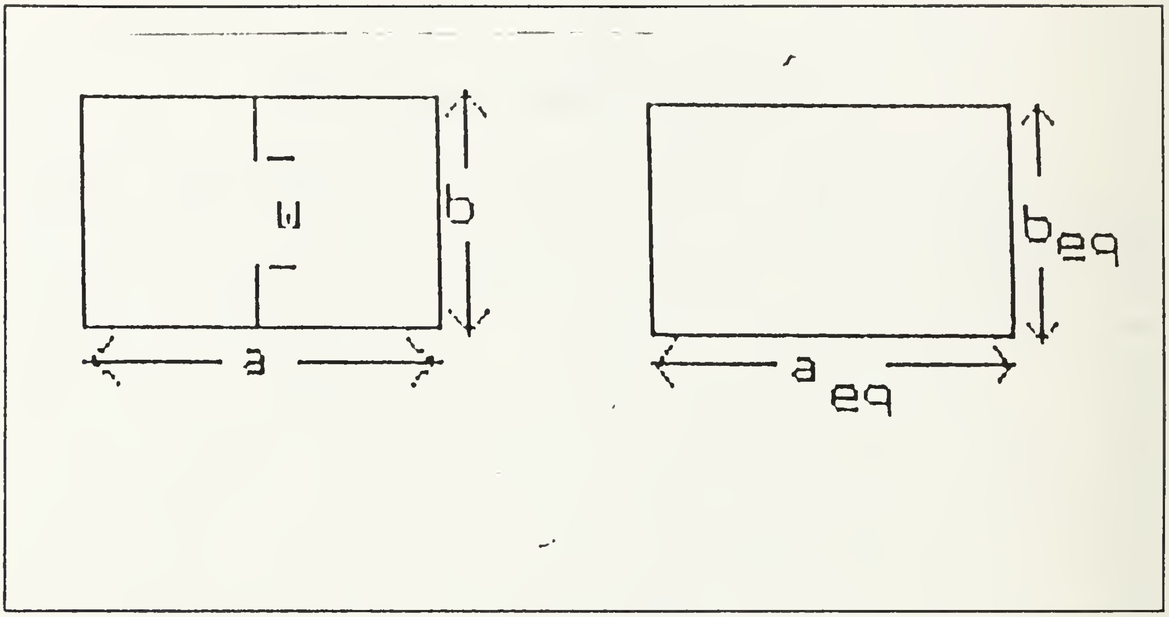


Figure 4. Homogeneous fin-line and equivalent rectangular waveguide structures.

b_{eq} which will have the same cutoff wavelength and impedance as expressed in equations 1(b). The choice of WR(90) fin-line was made because some experimental data existed for strips in homogeneous fin-line with $W/b < 1$ in the frequency range of 8.0-12.0 GHz.

In equation (1), the values of $\frac{\lambda'}{\lambda}$ and Z_{0v} for each particular frequency and for various values of W/b were determined by using the spectral domain technique for WR(90) fin-line.

Table 1 on page 7 shows the computed values of $\frac{\lambda'}{\lambda}$ and Z_{0v} for $W/b = 0.5$. Similar results for $W/b = 1.0, 0.25, 0.2, 0.1, 0.05, 0.02, 0.01$ are tabulated in Table 8 in Appendix A. Then, by using equation (1), the values of λ_c and $Z_{0v\infty}$ for each frequency were calculated as shown in Table 2 on page 7. This table gives the values of λ_c and $Z_{0v\infty}$ for the frequency interval 8.0-12.0 GHz.

In order to find the values of a_{eq}/a and b_{eq}/b to design our model we use the equations:

Table 1. Numerical values of $\frac{\lambda'}{\lambda}$ and Z_{0v} for W/b = 0.5.

Frequency	$\frac{\lambda'}{\lambda}$	Z_{0v}	W/b
8.0000	1.4665	424.2608	0.5
8.5000	1.3787	398.8695	0.5
9.0000	1.3165	380.7870	0.5
9.5000	1.2683	367.2257	0.5
10.0000	1.2344	356.7146	0.5
10.5000	1.2032	348.5253	0.5
11.0000	1.1806	341.7068	0.5
11.5000	1.1608	336.2265	0.5
12.0000	1.1466	331.0608	0.5

Table 2. Calculated values of cutoff wavelength and characteristic impedance vs. W/b for WR(90) fin-line.

W/b	λ_c	Z_{ov}
1.0	1.8	334.80
0.5	2.02	289.32
0.25	2.32	230.89
0.2	2.42	215.04
0.1	2.71	175.65
0.05	2.98	147.43
0.02	3.30	121.41
0.01	3.42	108.72

$$\frac{a_{eq}}{a} = \frac{\lambda_c}{2a} \tag{2a}$$

$$\frac{b_{eq}}{b} = \left(\frac{Z_{0v\infty}}{\eta_0}\right)\left(\frac{a_{eq}}{a}\right)\left(\frac{a}{2b}\right) \tag{2b}$$

where: $\eta_0 = 120\pi$

a = 900 mils

b = 400 mils.

Equations 2(a) and 2(b) are general equations for any value of a and b, which have been derived by Knorr, so we can use them for the paricular case where the relationship between the fin-line shield dimensions is b/a = 4/9.

Table 3. Calculated values of a_{eq} /a and b_{eq}/bvs. W/b for WR(90) fin-line.

W/b	a_{eq} /a	b_{eq} /b
1.00	1.00	1.0000
0.5	1.12	0.9687
0.25	1.29	0.8888
0.2	1.34	0.8624
0.1	1.50	0.7892
0.05	1.65	0.7285
0.02	1.85	0.6623
0.01	1.90	0.6164

The computed values are tabulated in Table 3. Figure 5 on page 9 and Figure 6 on page 10 show the plots of a_{eq}/a and b_{eq} /b vs. W/b respectively, where by using a best fit curve program we determined the following polynomials of 5th degree.

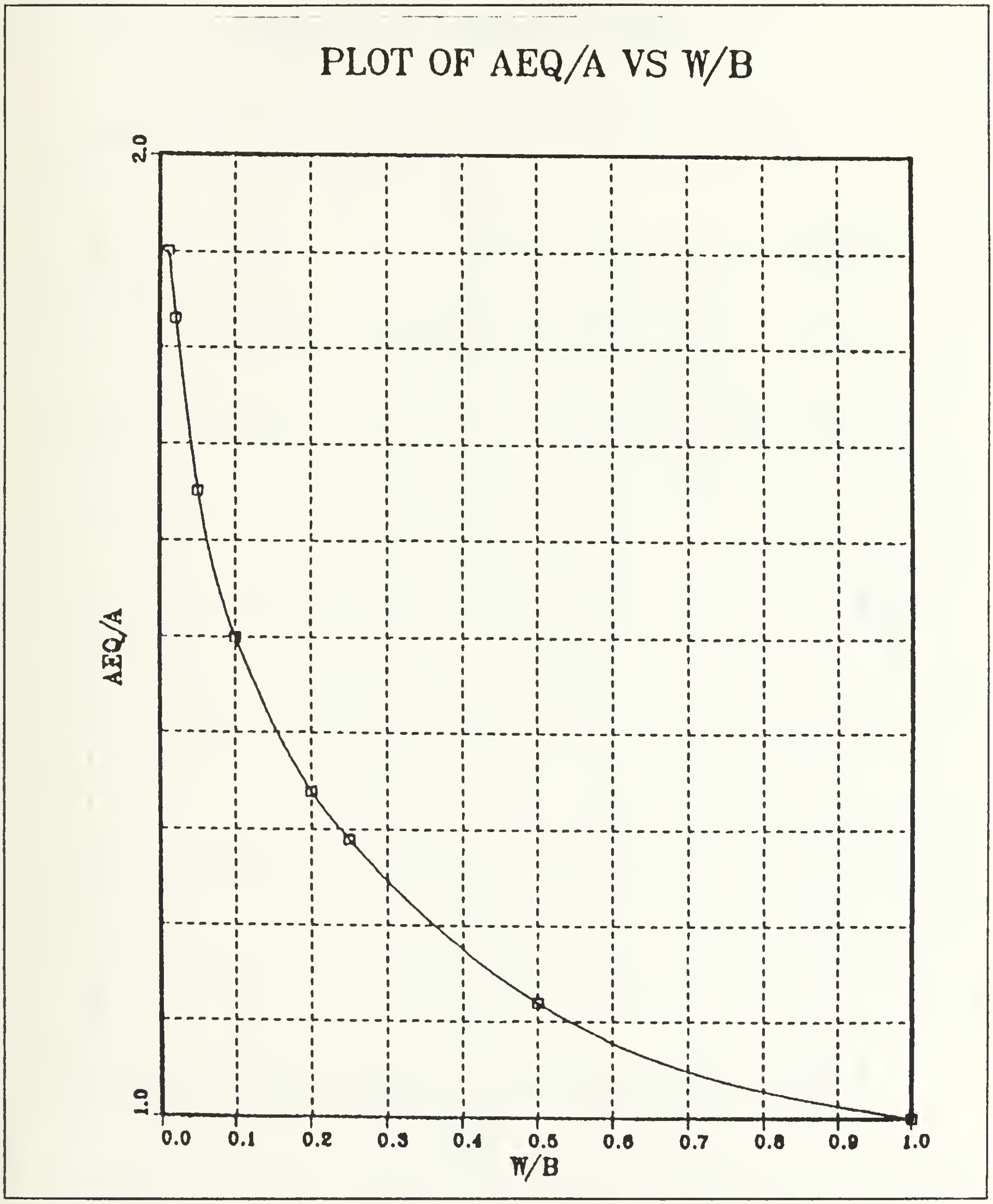


Figure 5. Plot of a_{eq}/a vs. W/b for a WR(90) fin-line.

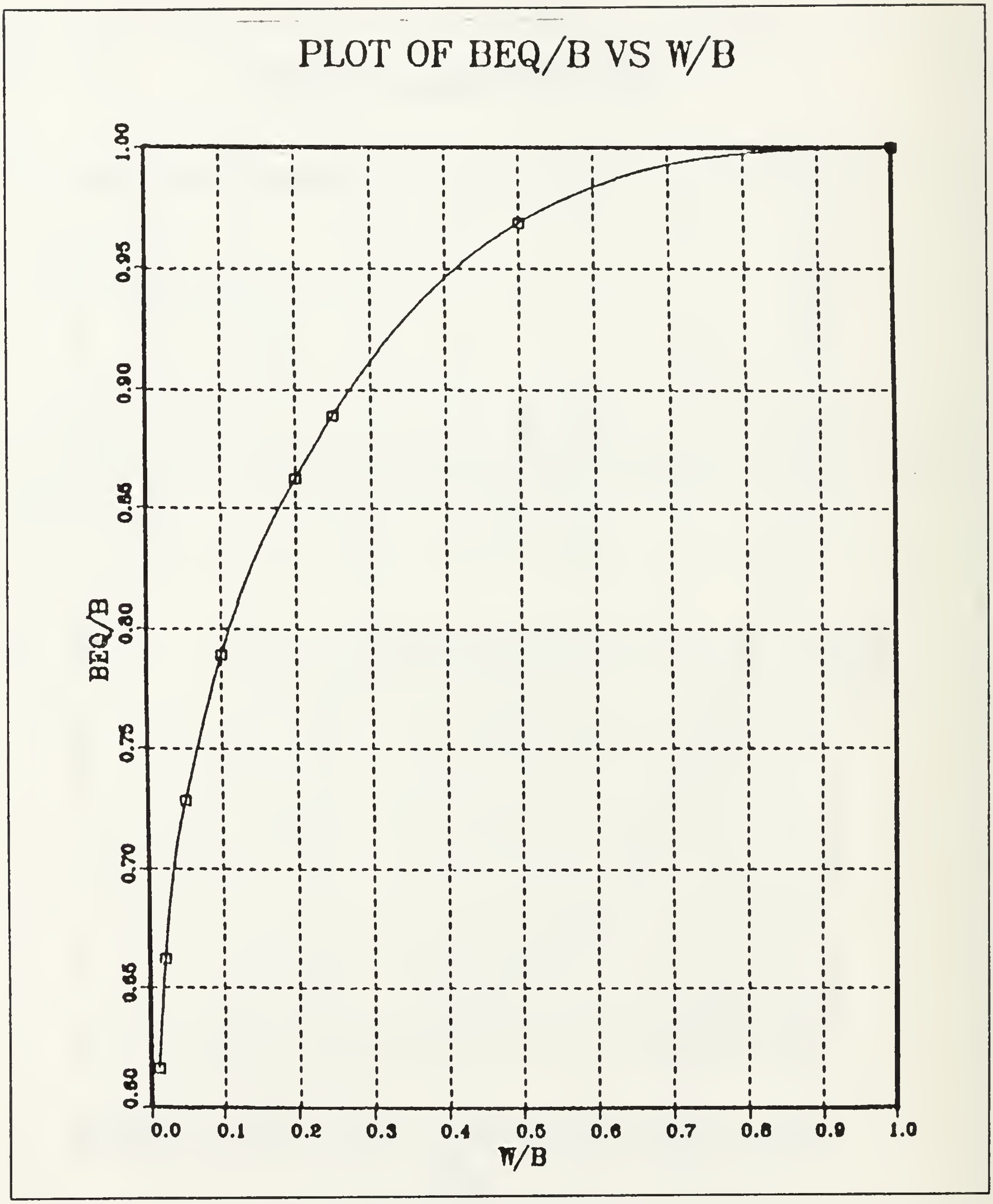


Figure 6. Plot of b_{eq}/b vs. W/b for a WR(90) fin-line.

$$\frac{a_{eq}}{a} = -247.3607\left(\frac{W}{b}\right)^5 + 471.5724\left(\frac{W}{b}\right)^4 - 289.3820\left(\frac{W}{b}\right)^3 + 74.0446\left(\frac{W}{b}\right)^2 - 9.8651\left(\frac{W}{b}\right) + 1.9909 \tag{3}$$

$$\frac{b_{eq}}{b} = 160.6892\left(\frac{W}{b}\right)^5 - 300.4026\left(\frac{W}{b}\right)^4 + 176.6337\left(\frac{W}{b}\right)^3 - 41.2604\left(\frac{W}{b}\right)^2 + 4.7638\left(\frac{W}{b}\right) + 0.5763 \tag{4}$$

These polynomials will be used to design the model of the fin-line structure.

III. MODELING AN INDUCTIVE STRIP IN HOMOGENEOUS FIN-LINE

The inductive strip in fin-line is used to construct simple resonators as well as more complicated multi-resonator filters. The geometry for an inductive strip is illustrated in Figure 2, Chapter 1.

The scattering coefficients S_{11} and S_{21} are functions of strip width, fin separation, dielectric constant, and strip length. The inductive strip is lossless, reciprocal, and symmetric, so its scattering matrix is unitary with $S_{11} = S_{22}$ and $S_{12} = S_{21}$ The unitary property leads to:

$$|S_{21}| = [1 - |S_{11}|^2]^{\frac{1}{2}} \tag{5}$$

$$\vartheta_{12} = \vartheta_{11} \pm \frac{\pi}{2} \tag{6}$$

where, in (6), the minus (-) sign is chosen because the strip is inductive. [Ref. 5: pp. 1013]

Theoretically, the problem can be solved by applying the spectral-domain method to fin-line resonators which are end- coupled by a thin, lossless strip. This permits the scattering matrix of the strip to be computed as reported by Knorr and Deal [Ref. 5: pp. 1011].

Some experimental measurements have been made to validate the numerical data generated using the code written by Deal [Ref. 6]. To ease measurement difficulties, all measurements were made using X-band test structures. Shield size was 0.4x0.9 in WR(90) fin-line and the fins were centered in the shield. With no dielectric, it is easy to establish the reference planes required for the measurement. Figure 7 on page 14 and Figure 8 on page 15 show $|S_{11}|$ and $\angle S_{11}$ for different strip lengths in fin-line with W/b = 0.5. Curves are presented for T = 20, 50, 100, 200, and 500 mils. Similar data for W/b = 0.25 and W/b = 0.2 are shown in Figures 18-19 and Figures 20-21 respectively, in Appendix B.

The ultimate goal is to design a model of an inductive strip in a fin-line. Typically, fin-line has a dielectric substrate with a dielectric constant > 1, but this increases the complexity of the problem, so the first step is to work with homogeneous ($E_r = 1$) fin-line.

Figure 9 on page 16 shows the circuit model of the inductive strip in fin- line, where T is the strip length and L is the inductance. As described in [Ref. 7.], the dimensions of the waveguide will be $a_{eq}/2$ and b_{eq} which are evaluated by using the computed values of λ_c and $Z_{0v\infty}$ from Table 3 on page 8 for each different value of W/b. The computed values of a_{eq} and b_{eq} will be used with the existing numerical and experimental data for strips in WR(90) fin-line with W/b < 1 to build a circuit model for the strips.

The computed scattering coefficients from the Tables 4, 8 and 9 were used to create a data file for W/b = 0.5, 0.25, 0.2 and for T = 20, 50, 100, 200, and 500 mils respectively as shown in Table 5 and Tables 10-23 in Appendix A. A TOUCHSTONE circuit file then was created to compute the scattering coefficients of the circuit model as shown in Figure 10 on page 17and Figure 11 on page 18.

Table 5. TOUCHSTONE data file of scattering coefficients for W/b = 0.5 T = 100 mils.

```
! SCATTERING PARAMETERS:

! FREQ /S11/     <S11     /S21/    <S21      /S12/    <S12     /S22/    <S22

8.0   .9649   153.6750  .2627   63.6750   .2627   63.6750  .9649   153.6750
8.5   .9517   149.4281  .3069   59.4281   .3069   59.3069  .9517   149.4281
9.0   .9367   145.2937  .3500   55.2937   .3500   55.2937  .9367   145.2937
9.5   .9193   141.5109  .3935   51.5109   .3935   51.5109  .9193   141.5109
10.0  .9002   136.8422  .4355   46.8422   .4355   46.8422  .9002   136.8422
10.5  .8776   133.3406  .4794   43.3406   .4794   43.3406  .8776   133.3406
11.0  .8539   129.0234  .5204   39.0234   .5204   39.0234  .8539   129.0234
11.5  .8269   125.9875  .5623   35.9875   .5623   35.9875  .8269   125.9875
12.0  .7975   120.1500  .6034   30.1500   .6034   30.1500  .7975   120.1500
```

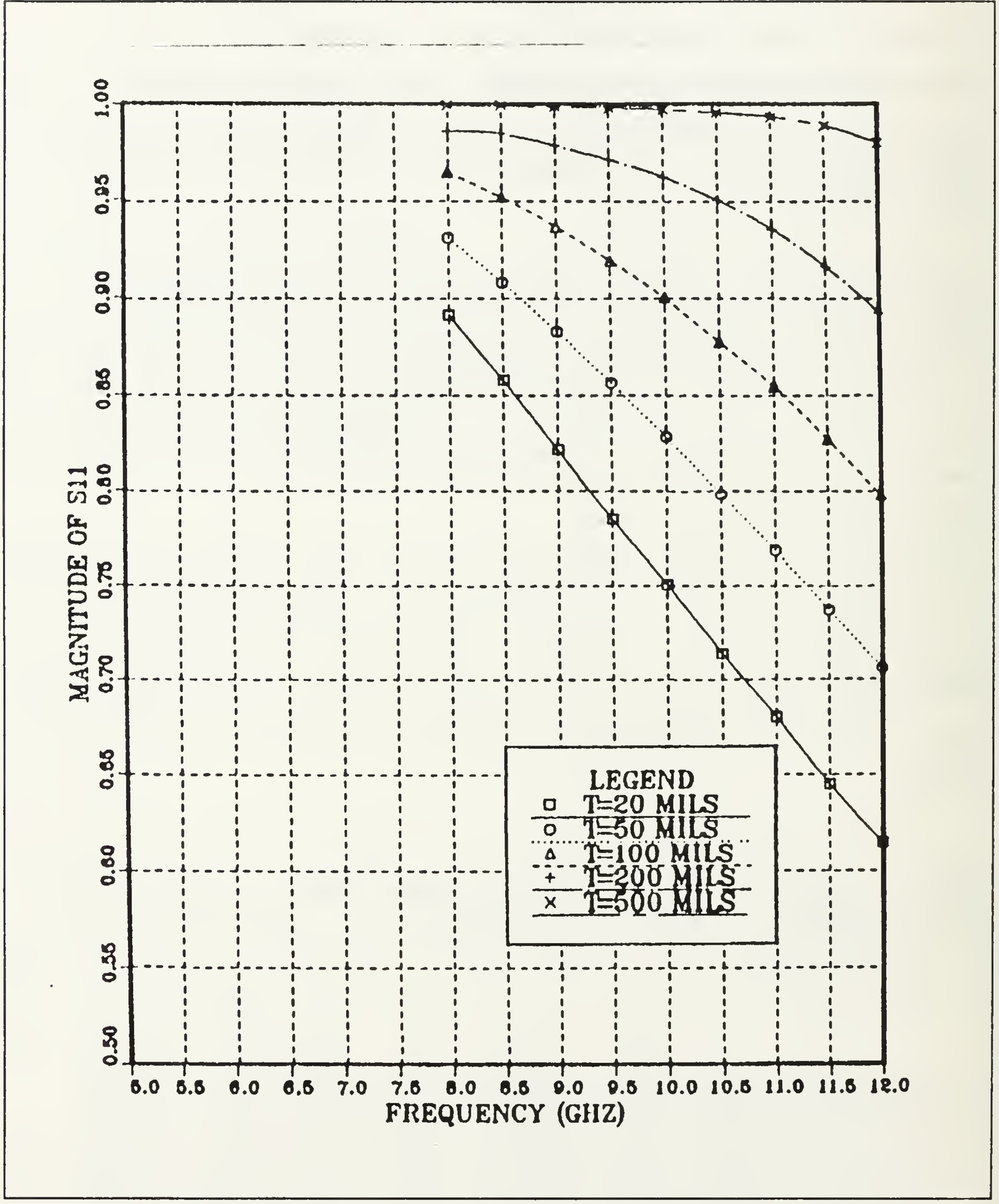


Figure 7. $|S_{11}|$ vs. frequency for inductive strips centered in WR(90) fin-line. W/b = 0.5, $E_{r2} = 1$.

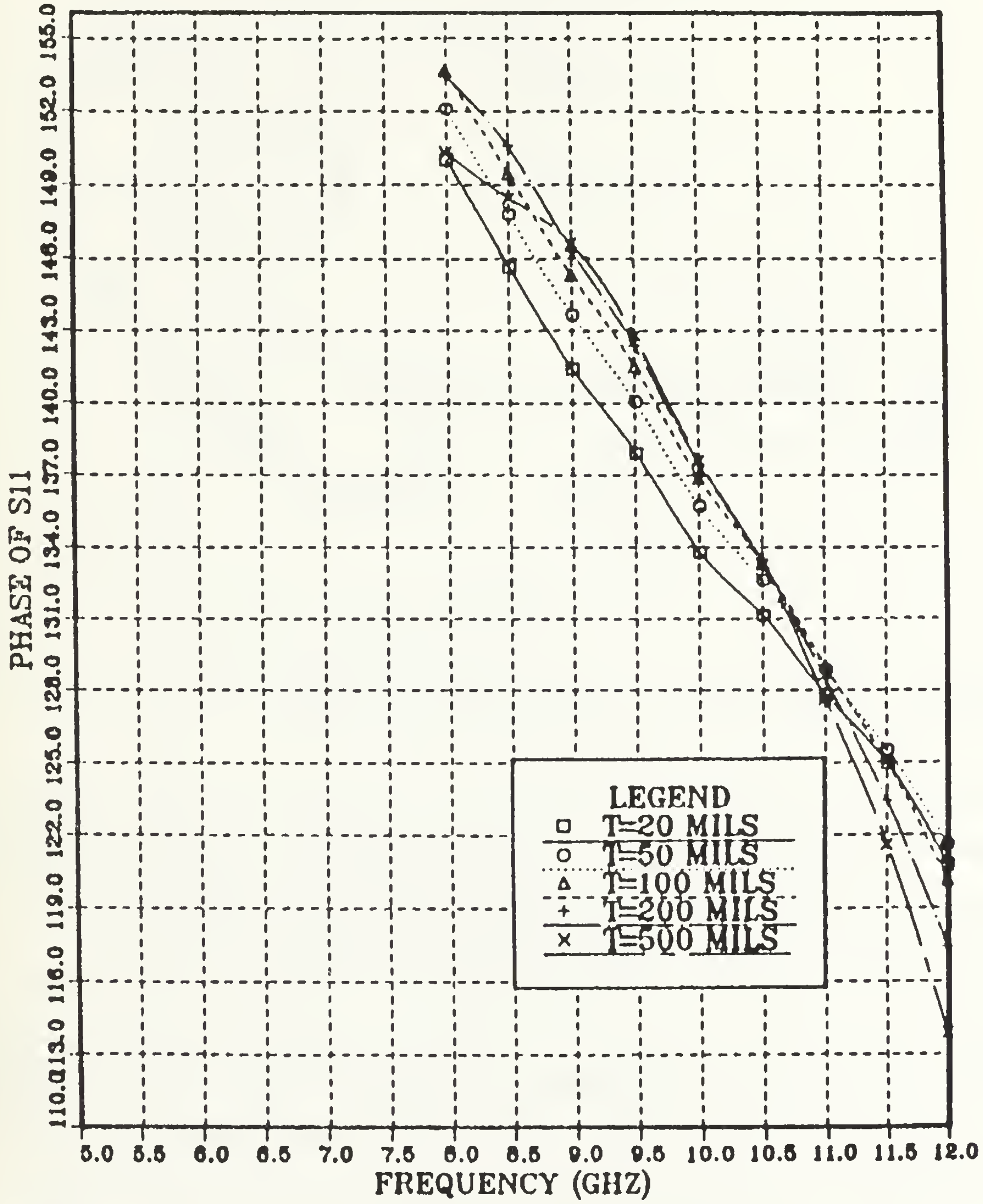


Figure 8. θ_{11} vs. frequency for inductive strips centered in WR(90) fin-line. W/b = 0.5, $E_{r2} = 1$.

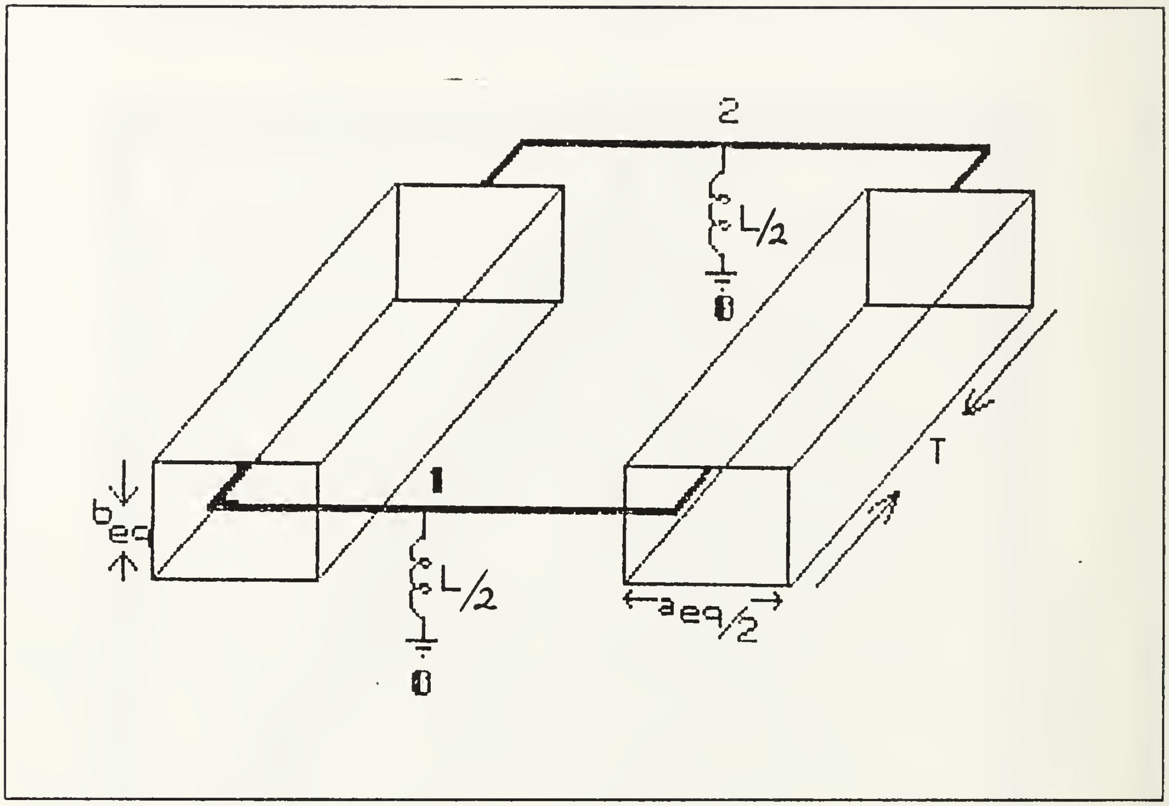
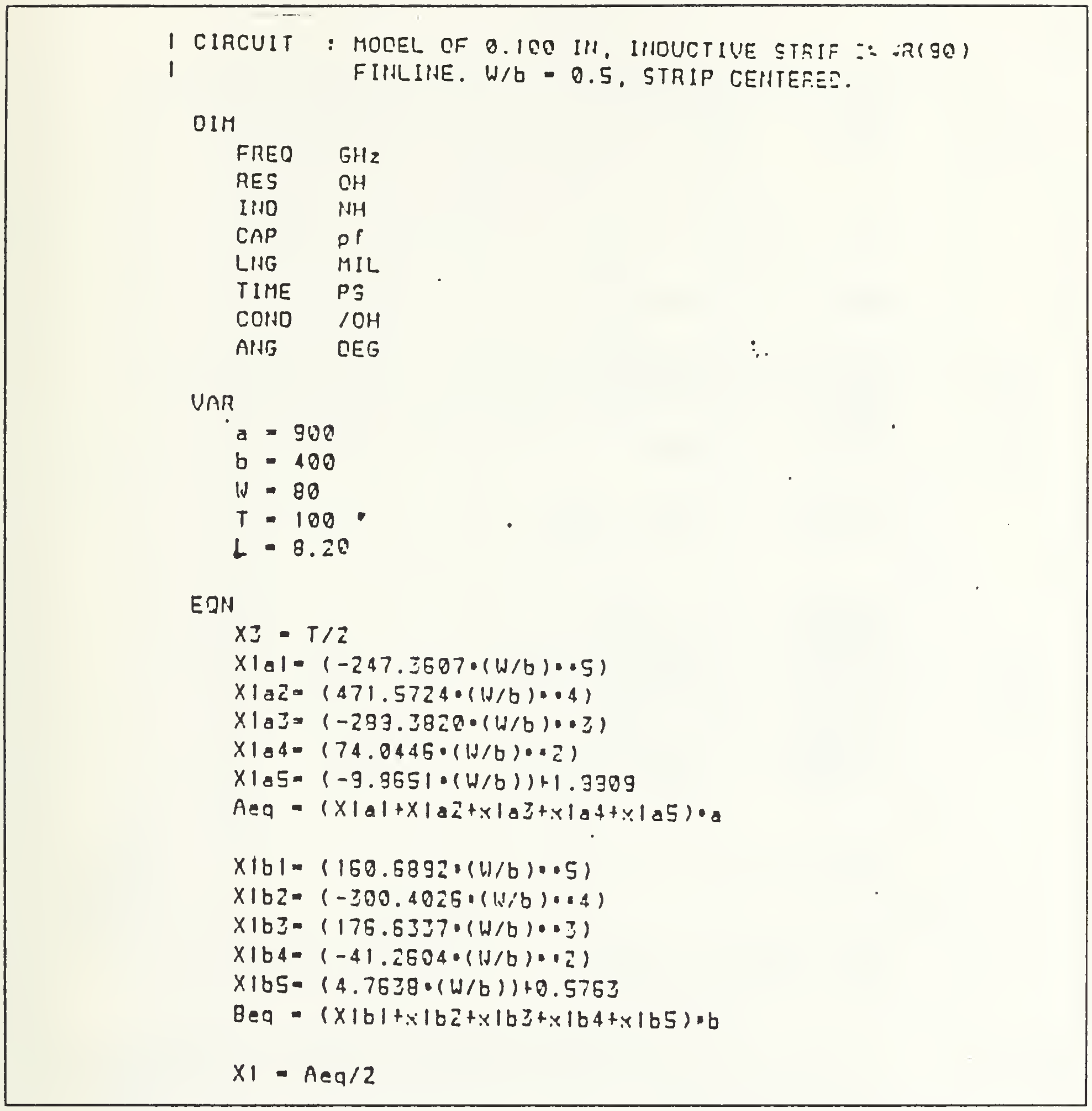


Figure 9. Circuit model of an inductive strip in fin-line.

Our goal is to match the scattering characteristics of the strip model to the computed scattering coefficients. By changing the value of the inductance L, we can find the value for which we obtain the best fit to the computed data.

The comparisons between the computed scattering coefficients and those predicted by the model for the case of W/b = 0.5 and T = 100 mils are illustrated in Figure 12 on page 19 and Figure 13 on page 20 which show the magnitude and phase curves respectively. These curves were made by using the TOUCHSTONE Microwave Circuit Simulator marketed by EEsof, Inc., Westlake Village, CA. By observing the phase curve in Figure 12 we can see that the error is about 3-4 % for the choice L = 8.2 nH.

Figure 14 on page 21 shows a Smith chart plot of calculated scattering coefficients S_{11} and S_{12} and those predicted by the model for the particular case of W/b = 0.5 and T = 100 mils.



```
! CIRCUIT  : MODEL OF 0.100 IN, INDUCTIVE STRIP IN WR(90)
!             FINLINE. W/b = 0.5, STRIP CENTERED.

 DIM
    FREQ    GHz
    RES     OH
    IND     NH
    CAP     pf
    LNG     MIL
    TIME    PS
    COND    /OH
    ANG     DEG

 VAR
    a = 900
    b = 400
    W = 80
    T = 100
    L = 8.20

 EQN
    X3 = T/2
    X1a1= (-247.3607*(W/b)**5)
    X1a2= (471.5724*(W/b)**4)
    X1a3= (-293.3820*(W/b)**3)
    X1a4= (74.0446*(W/b)**2)
    X1a5= (-9.9651*(W/b))+1.3309
    Aeq = (X1a1+X1a2+x1a3+x1a4+x1a5)*a

    X1b1= (160.6892*(W/b)**5)
    X1b2= (-300.4026*(W/b)**4)
    X1b3= (176.6337*(W/b)**3)
    X1b4= (-41.2604*(W/b)**2)
    X1b5= (4.7638*(W/b))+0.5763
    Beq = (X1b1+x1b2+x1b3+x1b4+x1b5)*b

    X1 = Aeq/2
```

Figure 10. TOUCHSTONE circuit file computing the scattering coefficients of the circuit model (part 1).

Similar plots can be obtained for W/b=0.5, 0.25, 0.2, and T=20, 50, 100, 200 and 500 mils in magnitude, phase, and on the Smith chart. These plots are illustrated in Figures 22-63 respectively and were obtained by using the corresponding optimum value of L for each case. Table 6 on page 23 shows all the predicted values of L for each particular case, along with those values of L for

```
CKT
   IND     1  0  L^L
   RWG     1  2  A ^ X1   B ^ Beq   L ^ X3   ER = 1   RHO = 1
   DEF2P   1  2  A

    A      1  2
    A      1  2
    A      3  2
    A      3  2
   DEF2P   1  3  STRIPMOD

   S2PA    1  2     0  T90wbS10.s2p
   DEF2P   1  2  T90wbS10

   RWGT    1     A ^ Aeq   B ^ Beq    ER = 1   RHO = 1
   DEF1P   1     WEDGE

TERM
   STRIPMOD      WEDGE  WEDGE

OUT
   T90wbS10      S11   SC2
 ! T90WBS10      S21   SC2
 ! T90wbS10      MAG[S11]    GR1
 ! T90wbS10      ANG[S11]    GR2
 ! STRIPMOD     S11   SC2
 ! STRIPMOD      S21   SC2
 ! STRIPMOD      MAG[S11]    GR1
 ! STRIPMOD      ANG[S11]    GR2

FREQ
   SWEEP   8.0  12.  0.5

GRID
   RANGE   8.0  12.  1.0
    GR1    0.0   1.  0.1
    GR2    30   100  5.0
```

Figure 11. TOUCHSTONE circuit file computing the scattering coefficients of the circuit model (part 2).

W/b = 1.0 as determined by Knorr [Ref. 7: pp. 13]. The table shows that as strip length increases from T = 20 to 500 mils, the value of L decreases. As W/b decreases for each particular value of T, then again the inductance decreases.

Having obtained the inductance for the various strip lengths (T = 20, 50, 100, 200, 500 mils) and for various values of W/b modeled previously, it is a simple matter to explore the possibility that the curve L(T) can be approximated by

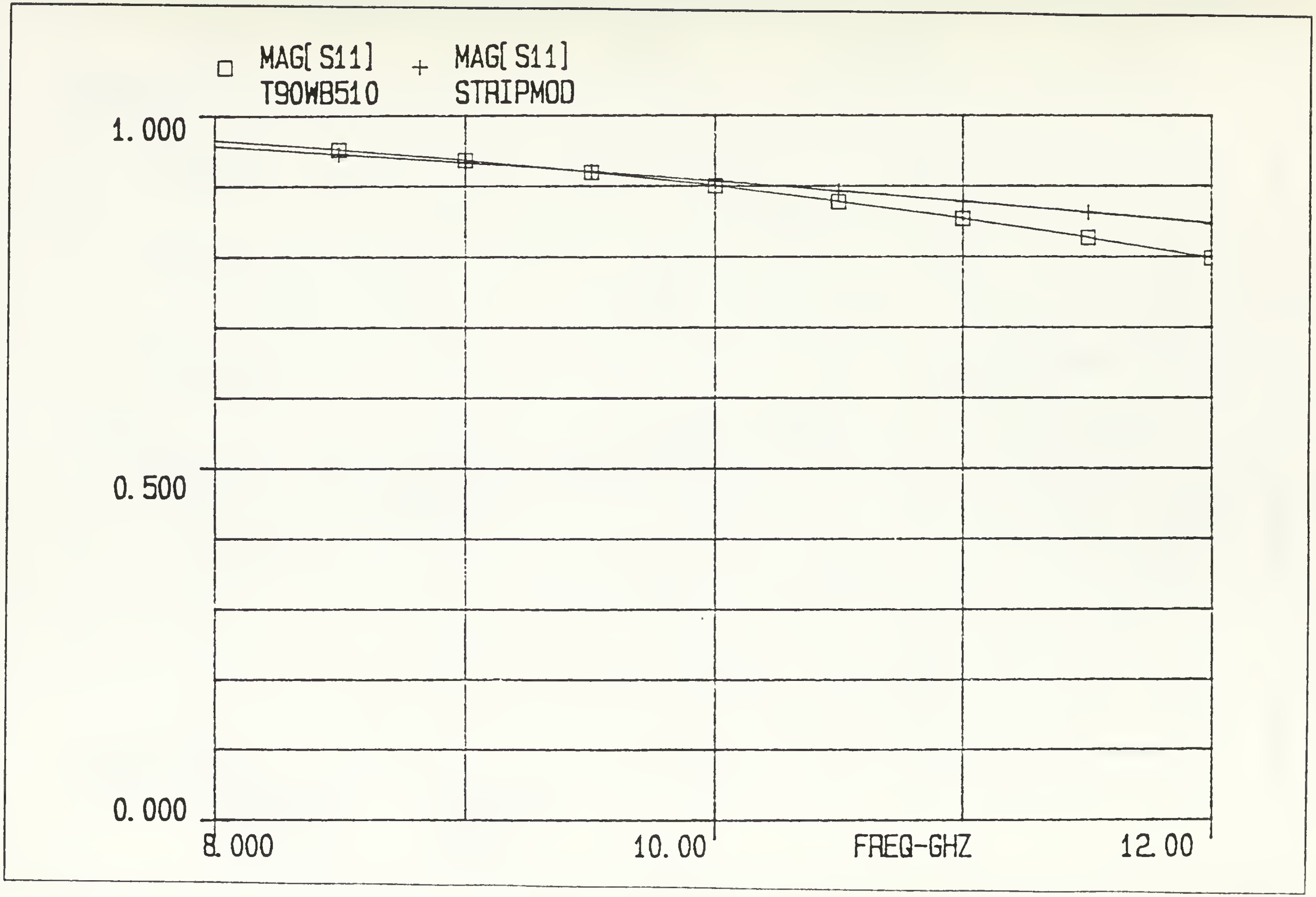


Figure 12. Computed and predicted values of $|S_{11}|$ vs. frequency for a T = 100 mils inductive strip centered in WR(90) waveguide W/b = 0.5, E_{r2} = 1. Model inductance L = 8.2 nH.

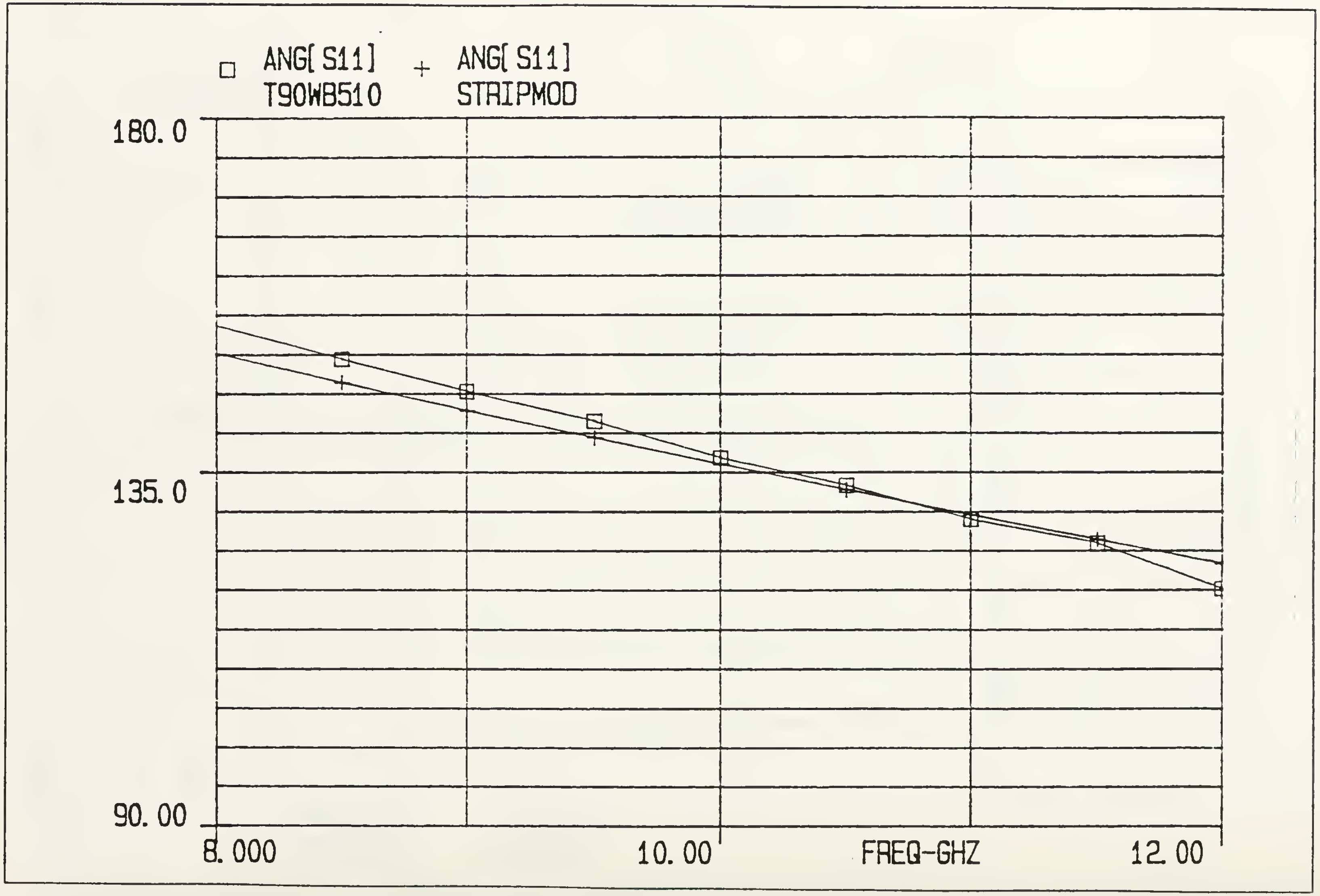


Figure 13. Computed and predicted values of θ_{11} vs. frequency for a T = 100 mils inductive strip centered in WR(90) waveguide W/b = 0.5, E_{r2} = 1. Model inductance L = 8.2 nH.

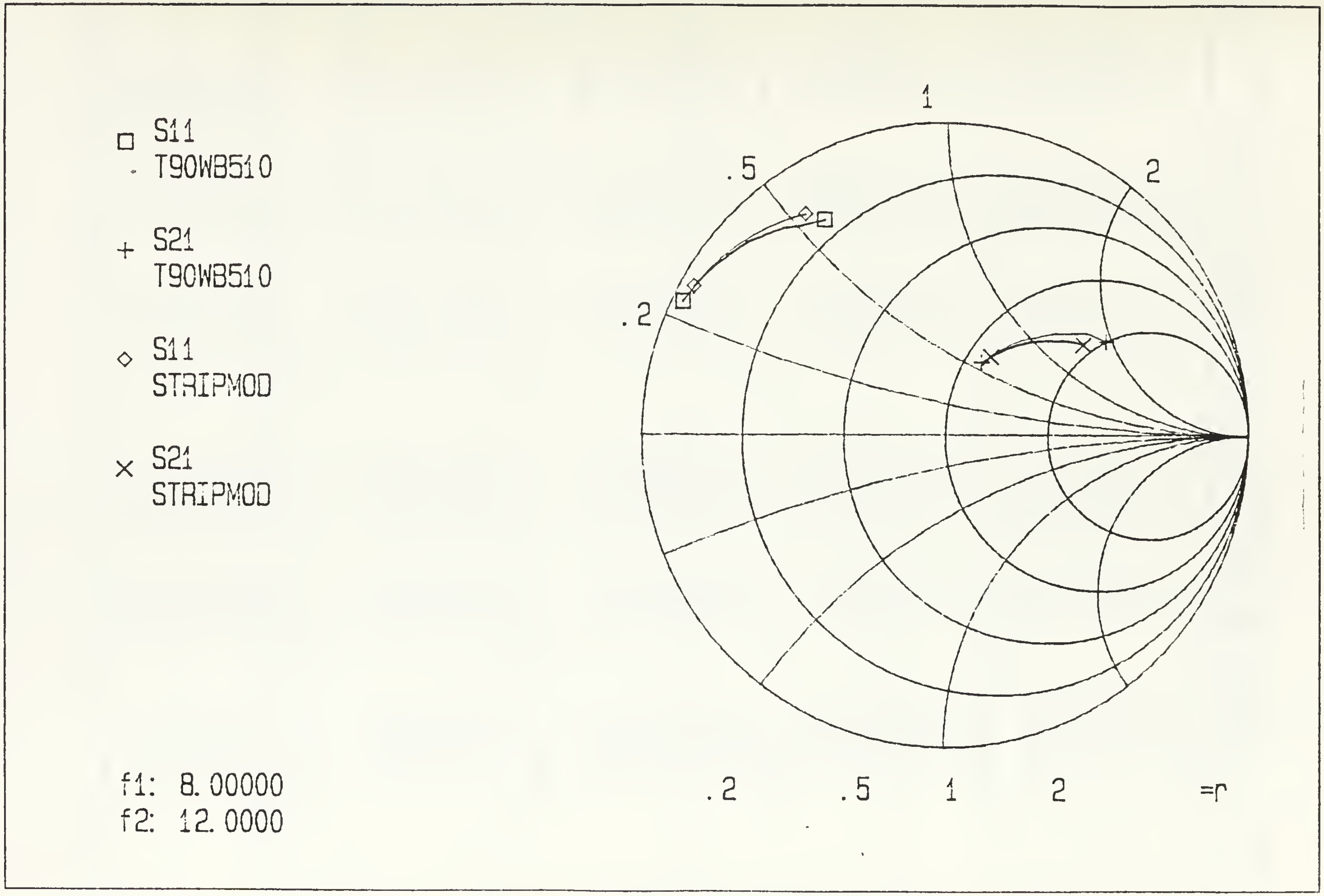


Figure 14. Smith chart plot of computed and predicted values of S11 and S_{21} for a T = 100 mil inductive strip centered in WR(90) waveguide, W/b = 0.5, E_{r2} = 1. Model inductance L = 8.2 nH.

Table 4. Computed scattering coefficients for WR(90) fin-line for W/b = 0.5 and T = 20, 50, 100, 200, and 500 mils (D = 10 mils).

FREQUENCY	S11 Mag.	S11 Phase	S12 Mag.	S12 Phase	T OVER D
8.0000	0.8918	150.0188	0.4525	60.0187	2.0000
8.5000	0.8576	145.6312	0.5143	55.6312	2.0000
9.0000	0.8217	141.4125	0.5700	51.4125	2.0000
9.5000	0.7852	137.8969	0.6193	47.8969	2.0000
10.0000	0.7508	133.8047	0.6606	43.8047	2.0000
10.5000	0.7140	131.1328	0.7001	41.1328	2.0000
11.0000	0.6799	127.8141	0.7333	37.8141	2.0000
11.5000	0.6451	124.9875	0.7641	34.9875	2.0000
12.0000	0.6150	120.8100	0.7940	30.8100	2.0000

FREQUENCY	S11 Mag.	S11 Phase	S12 Mag.	S12 Phase	T OVER D
8.0000	0.9312	152.0859	0.3645	62.0859	5.0000
8.5000	0.9079	147.7547	0.4191	57.7547	5.0000
9.0000	0.8832	143.6344	0.4690	53.6344	5.0000
9.5000	0.8560	140.0484	0.5170	50.0484	5.0000
10.0000	0.8283	135.6750	0.5603	45.6750	5.0000
10.5000	0.7981	132.6094	0.6026	42.6094	5.0000
11.0000	0.7685	128.8687	0.6399	38.8687	5.0000
11.5000	0.7371	125.5500	0.6757	35.5500	5.0000
12.0000	0.7062	121.6406	0.7080	31.6406	5.0000

FREQUENCY	S11 Mag.	S11 Phase	S12 Mag.	S12 Phase	T OVER D
8.0000	0.9649	153.6750	0.2627	63.6750	10.0000
8.5000	0.9517	149.4281	0.3069	59.4281	10.0000
9.0000	0.9367	145.2937	0.3500	55.2937	10.0000
9.5000	0.9193	141.5109	0.3935	51.5109	10.0000
10.0000	0.9002	136.8422	0.4355	46.8122	10.0000
10.5000	0.8776	133.3406	0.4794	43.3406	10.0000
11.0000	0.8539	129.0234	0.5204	39.0234	10.0000
11.5000	0.8269	124.9875	0.5623	34.9875	10.0000
12.0000	0.7975	120.1500	0.6034	30.1500	10.0000

FREQUENCY	S11 Mag.	S11 Phase	S12 Mag.	S12 Phase	T OVER D
8.0000	0.9862	153.4641	0.1656	63.4641	20.0000
8.5000	0.9848	150.5531	0.1736	60.5531	20.0000
9.0000	0.9789	146.3062	0.2045	56.3062	20.0000
9.5000	0.9714	142.3406	0.2375	52.3062	20.0000
10.0000	0.9625	137.4609	0.2714	47.4609	20.0000
10.5000	0.9501	133.4250	0.3120	43.4250	20.0000
11.0000	0.9355	128.4750	0.3532	38.4750	20.0000
11.5000	0.9161	123.4125	0.4010	33.4125	20.0000
12.0000	0.8928	117.4078	0.4505	27.4078	20.0000

FREQUENCY	S11 Mag.	S11 Phase	S12 Mag.	S12 Phase	T OVER D
8.0000	0.9999	150.3000	0.0255	60.3000	50.0000
8.5000	0.9995	148.4437	0.0355	58.4437	50.0000
9.0000	0.9989	146.5875	0.0464	56.5875	50.0000
9.5000	0.9984	142.7625	0.0557	52.7625	50.0000
10.0000	0.9975	137.5875	0.0709	47.5875	50.0000
10.5000	0.9960	133.3125	0.0895	43.3125	50.0000
11.0000	0.9934	127.6172	0.1151	37.6172	50.0000
11.5000	0.9887	121.6266	0.1501	31.6266	50.0000
12.0000	0.9802	113.8641	0.1980	23.9641	50.0000

Table 6. Predicted values of L vs. W/b for WR(90) fin-line and strip length T using the polynomial form.

W/b	T=20 mils	T=50 mils	T=100mils	T=200 mils	T=500 mils
1.00	27.00	23.00	20.000	17.00	16.00
0.5	10.70	9.30	8.200	7.20	5.90
0.25	6.60	5.65	5.005	4.20	3.82
0.2	4.89	4.18	3.550	3.06	2.70

some simple analytical expression. A good fit to these data is the polynomial form of 5th degree, which can be found using a best fit curve program:

a) for W/b = 1.0:

$$L = 0.0003(\frac{T}{D})^5 - 0.0270(\frac{T}{D})^4 + 0.6999(\frac{T}{D})^3 - 6.8761(\frac{T}{D})^2 + 24.6634(\frac{T}{D})$$

b) for W/b = 0.5:

$$L = 0.0001(\frac{T}{D})^5 - 0.0105(\frac{T}{D})^4 + 0.2729(\frac{T}{D})^3 - 2.6880(\frac{T}{D})^2 + 9.7166(\frac{T}{D})$$

c) for W/b = 0.25:

$$L = 0.0001(\frac{T}{D})^5 - 0.0066(\frac{T}{D})^4 + 0.1711(\frac{T}{D})^3 - 1.6789(\frac{T}{D})^2 + 6.0250(\frac{T}{D})$$

d) for W/b = 0.2:

$$L = 0.0001(\frac{T}{D})^5 - 0.0048(\frac{T}{D})^4 + 0.1256(\frac{T}{D})^3 - 1.2381(\frac{T}{D})^2 + 4.4567(\frac{T}{D})$$

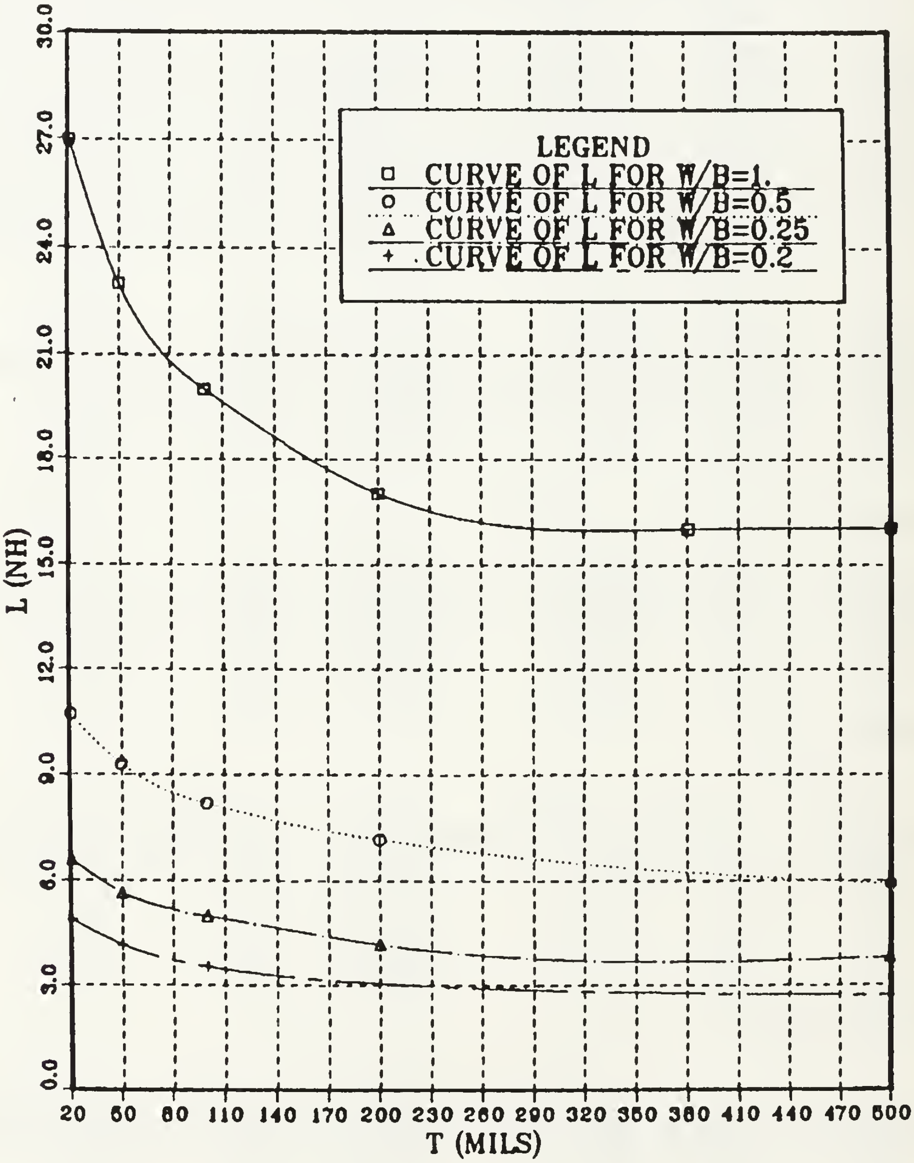


Figure 15. Plots of the model inductance L as a polynomial function of the strip length T, for W/b = 1.0, 0.5, 0.25, 0.2.

Figure 15 on page 24 shows the graphs of the model inductance L as a function of T.

Another possible form which can fit these data is an exponential curve which has the following form for each value of W/b:

a) For $W/b=1.0$: $L = 16 + 14.4 * \exp(-T/75)$ nH

b) for $W/b=0.5$: $L = 5.9 + 5.769 * \exp(-T/108.738)$ nH

c) for $W/b=0.25$: $L = 3.82 + 3.44 * \exp(-T/93.8187)$ nH

d) for $W/b=0.2$: $L = 2.7 + 2.7746 * \exp(-T/84.529)$ nH

where strip length T is in mils.

We can see that as W/b decreases the value of the inductance decreases. This reflects the fact that as the space between the fins decreases, a strip of fixed length will reflect a higher fraction of the incident power. Table 7 shows the calculated values of L using these exponential formulas for each value of T. Figure 16 on page 26 shows the graphs of the model inductance L, as a function of the strip length T, for W/b = 1.0, 0.5, 0.25, 0.2. The values listed on Table 7 are circled on the graphs.

Table 7. Predicted values of L vs. W/b for WR(90) fin-line and strip length T using the exponential form.

W/b	T=20 mils	T=50 mils	T=100mils	T=200 mils	T=500 mils
1.00	27.000	23.000	20.0000	17.000	16.000
0.5	10.699	9.540	8.1900	6.816	5.958
0.25	6.599	5.839	5.0049	4.228	3.836
0.2	4.889	4.235	3.5499	2.960	2.707

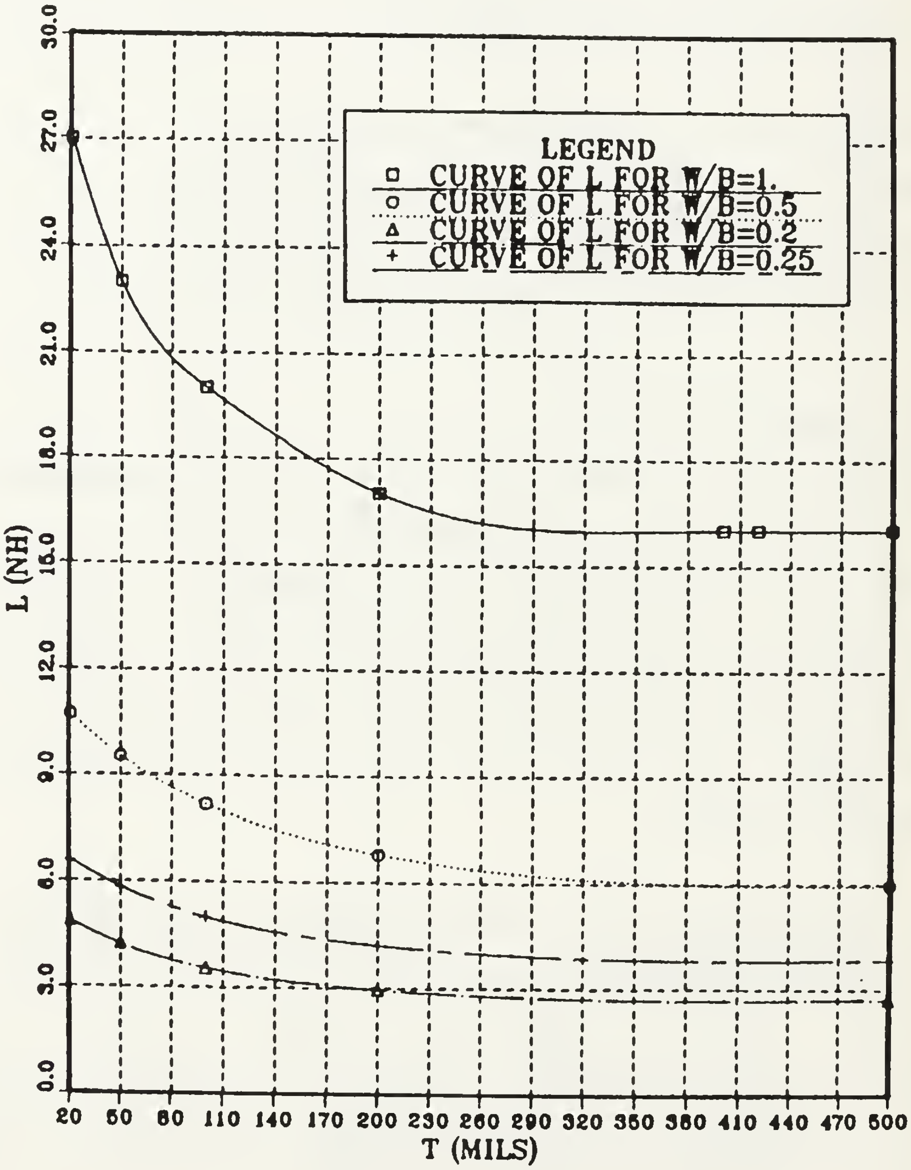


Figure 16. Plot of the model inductance L as an exponential function of the strip length T, for W/b = 1.0, 0.5, 0.25, 0.2.

Comparing the values of L between Table 6 on page 23 and Table 7, we see that there is a slight difference between them. Figure 17 on page 27 shows the difference between the exponential and polynomial form for each value of W/b.

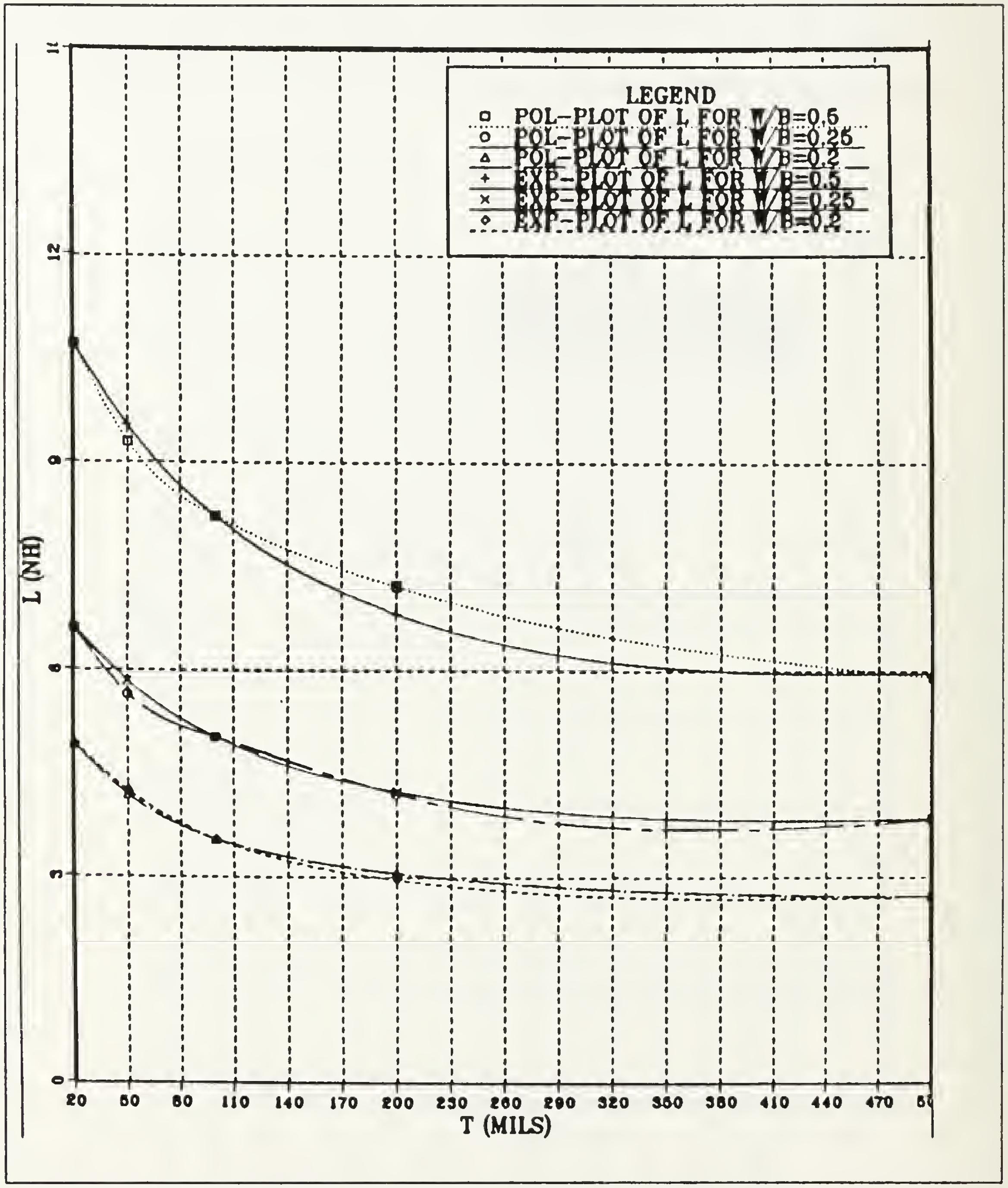


Figure 17. Difference between the exponential and polynomial plots of the model inductance L, for W/b = 0.5, 0.25, 0.2.

IV. CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

This thesis describes a circuit model for an inductive strip in fin-line for the homogeneous case, where $E_{r2} = 1$ and any value of W/b in the range $0 < W/b \leq 1$ is permitted.

The characteristics of integrated fin-line transmission line are reviewed. Fin-line is compatible with batch- processing techniques and superior to microstrip in several respects at millimeter wavelengths. Relative to microstrip, fin-line can provide less stringent tolerances, greater freedom from radiation and higher mode propagation, better compatibility with hybrid devices, and simpler interfaces with waveguide instrumentation [Ref. 1: pp. 1209].

The models discussed here were determined for the 8-12 GHz frequency range using WR(90) waveguide for reasons related to availability of test instrumentation and ease of fabrication. It was in this frequency range that experimental data was available to verify the numerical data generated using Deal's code [Ref. 6]. Numerical data was used to develop the circuit model. X-band was chosen as a starting point to ensure that the model was based on accurate data. Thus the design of a fin-line model was needed for b/a = 4/9. The values of the cutoff wavelength and the high frequency impedance limit were determined for different values of W/b (W/b = 0.5, 0.25, 0.2, 0.1, 0.05, 0.02, 0.01) using spectral domain data.

The circuit model is elegant in its simplicity, consisting of parallel, below cutoff waveguide sections with lumped inductors at each end. The values of the equivalent dimensions were obtained by using equations (2), which were derived by Prof. Knorr for various values of W/b.

The model was developed using data for strips with lengths of T = 20, 50, 100, 200, and 500 mils. The value of lumped inductance was determined by varying L to obtain the best agreement between the value of $\angle S_{11}$ predicted by the circuit model and the value of $\angle S_{11}$ computed numerically for strips of various lengths in WR(90) fin-line. Good agreement was obtained in all cases and the optimum values of inductance were used to determine a function L(T).

The good agreement that has been obtained between model data and numerical data suggests that the model may be used to design millimeter filters for communication systems, high-resolution imaging, collision avoidance radars, and enviromental monitoring equipment [Ref. 1: pp. 1215].

B. RECOMMENDATIONS

As a result of the success achieved in the modeling effort reported here, there are several areas which appear fruitful for future investigation.

1. Develop a model for strips centered in finline with W/b = 0.1, 0.05, 0.02, 0.01, $E_{r2} = 1$.
2. Investigate the relationship of strip length to the coefficients of the polynomial which describes the function L(T).
3. Develop a model for inductive strips which are off- centered with $W/b < 1$, $E_{r2} = 1$.
4. Develop a model for the general case of a strip printed on a dielectric substrate with $W/b < 1$.

APPENDIX A. TABLES

Table 8. Computed scattering coefficients for WR(90) fin-line for W/b = 0.25 and T = 20, 50, 100, 200, and 500 mils (D = 10 mils).

FREQUENCY	S11 Mag.	S11 Phase	S12 Mag.	S12 Phase	T OVER D
8.0000	0.9314	155.5734	0.3640	65.5734	2.0000
8.5000	0.9134	152.0578	0.4070	62.0578	2.0000
9.0000	0.8938	149.3438	0.4485	59.3438	2.0000
9.5000	0.8720	146.5172	0.4895	56.5172	2.0000
10.0000	0.8494	143.7188	0.5277	53.7188	2.0000
10.5000	0.8256	140.4563	0.5643	50.4563	2.0000
11.0000	0.7992	138.1219	0.6010	48.1219	2.0000
11.5000	0.7725	134.9719	0.6350	44.9719	2.0000
12.0000	0.7447	132.3562	0.6674	42.3562	2.0000

FREQUENCY	S11 Mag.	S11 Phase	S12 Mag.	S12 Phase	T OVER D
8.0000	0.9591	157.0078	0.2832	67.0078	5.0000
8.5000	0.9476	153.5625	0.3195	63.5625	5.0000
9.0000	0.9347	150.9609	0.3553	60.9609	5.0000
9.5000	0.9202	148.1344	0.3915	58.1344	5.0000
10.0000	0.9035	145.1250	0.4287	55.1250	5.0000
10.5000	0.8855	141.8062	0.4647	51.8062	5.0000
11.0000	0.8648	139.1906	0.5021	49.1906	5.0000
11.5000	0.8423	135.6187	0.5389	45.6187	5.0000
12.0000	0.8174	132.5531	0.5760	42.5531	5.0000

FREQUENCY	S11 Mag.	S11 Phase	S12 Mag.	S12 Phase	T OVER D
8.0000	0.9755	156.6281	0.2198	66.6255	10.0000
8.5000	0.9739	154.5188	0.2270	64.5188	10.0000
9.0000	0.9667	151.8750	0.2561	61.8750	10.0000
9.5000	0.9577	148.9781	0.2877	58.9781	10.0000
10.0000	0.9472	145.8984	0.3207	55.8984	10.0000
10.5000	0.9351	142.3266	0.3544	52.3266	10.0000
11.0000	0.9201	139.4297	0.3917	49.4297	10.0000
11.5000	0.9023	135.4359	0.4311	45.4359	10.0000
12.0000	0.8808	131.6953	0.4736	41.6953	10.0000

FREQUENCY	S11 Mag.	S11 Phase	S12 Mag.	S12 Phase	T OVER D
8.0000	0.9900	157.9996	0.1350	67.9996	20.0000
8.5000	0.9895	154.8844	0.1400	64.8844	20.0000
9.0000	0.9893	152.3250	0.1460	62.3250	20.0000
9.5000	0.9858	149.3719	0.1678	59.3719	20.0000
10.0000	0.9812	146.2078	0.1932	56.2078	20.0000
10.5000	0.9749	142.2984	0.2225	52.2984	20.0000
11.0000	0.9664	138.9937	0.2570	48.9937	20.0000
11.5000	0.9551	134.4516	0.2964	44.4516	20.0000
12.0000	0.9394	129.9516	0.3429	39.9516	20.0000

FREQUENCY	S11 Mag.	S11 Phase	S12 Mag.	S12 Phase	T OVER D
8.0000	0.9999	153.3987	0.0141	63.3987	50.0000
8.5000	0.9998	152.5325	0.0190	62.5325	50.0000
9.0000	0.9996	150.8792	0.0283	60.8792	50.0000
9.5000	0.9994	148.5981	0.0346	58.5981	50.0000
10.0000	0.9988	146.1797	0.0491	56.1797	50.0000
10.5000	0.9980	142.1859	0.0628	52.1859	50.0000
11.0000	0.9966	138.5297	0.0824	48.5297	50.0000
11.5000	0.9941	133.2984	0.1088	43.2984	50.0000
12.0000	0.9889	127.7156	0.1484	37.7156	50.0000

Table 9. Computed scattering coefficients for WR(90) fin-line for W/b = 0.2 and T = 20, 50, 100, 200, and 500 mils (D = 10 mils).

FREQUENCY	S11 Mag.	S11 Phase	S12 Mag.	S12 Phase	T OVER D
8.0000	0.9416	157.4156	0.3367	67.4156	2.0000
8.5000	0.9266	154.4906	0.3761	64.4906	2.0000
9.0000	0.9103	151.7906	0.4140	61.7906	2.0000
9.5000	0.8922	148.5562	0.4516	58.5562	2.0000
10.0000	0.8725	145.8984	0.4886	55.8984	2.0000
10.5000	0.8511	143.3953	0.5250	53.3953	2.0000
11.0000	0.8282	140.8922	0.5605	50.8922	2.0000
11.5000	0.8036	138.1219	0.5951	48.1219	2.0000
12.0000	0.7780	135.0422	0.6283	45.0422	2.0000

FREQUENCY	S11 Mag.	S11 Phase	S12 Mag.	S12 Phase	T OVER D
8.0000	0.9653	158.6531	0.2613	68.6531	5.0000
8.5000	0.9559	155.7984	0.2936	65.7984	5.0000
9.0000	0.9456	153.2109	0.3253	63.2109	5.0000
9.5000	0.9336	150.0188	0.3583	60.0187	5.0000
10.0000	0.9197	147.2203	0.3926	57.2203	5.0000
10.5000	0.9041	144.6187	0.4273	54.6187	5.0000
11.0000	0.8861	141.8766	0.4636	51.8766	5.0000
11.5000	0.8658	138.7969	0.5004	48.7969	5.0000
12.0000	0.8437	135.3375	0.5369	45.3375	5.0000

FREQUENCY	S11 Mag.	S11 Phase	S12 Mag.	S12 Phase	T OVER D
8.0000	0.9793	159.2248	0.2000	69.2248	10.0000
8.5000	0.9770	156.2484	0.2134	66.2484	10.0000
9.0000	0.9725	154.0125	0.2327	64.0125	10.0000
9.5000	0.9656	150.7078	0.2601	60.7078	10.0000
10.0000	0.9565	147.8109	0.2917	57.8109	10.0000
10.5000	0.9463	145.0687	0.3232	55.0687	10.0000
11.0000	0.9333	142.0453	0.3590	52.0453	10.0000
11.5000	0.9179	138.6141	0.3967	48.6141	10.0000
12.0000	0.8991	134.5922	0.4377	44.5922	10.0000

FREQUENCY	S11 Mag.	S11 Phase	S12 Mag.	S12 Phase	T OVER D
8.0000	0.9935	159.1025	0.1138	69.1025	20.0000
8.5000	0.9925	156.9352	0.1222	66.9352	20.0000
9.0000	0.9915	154.6210	0.1301	64.6210	20.0000
9.5000	0.9885	151.0875	0.1513	61.0875	20.0000
10.0000	0.9847	148.0641	0.1743	58.0641	20.0000
10.5000	0.9794	145.0266	0.2018	55.0266	20.0000
11.0000	0.9723	141.7078	0.2339	51.7078	20.0000
11.5000	0.9623	137.7703	0.2719	47.7703	20.0000
12.0000	0.9486	132.9891	0.3165	42.9891	20.0000

FREQUENCY	S11 Mag.	S11 Phase	S12 Mag.	S12 Phase	T OVER D
8.0000	0.9998	152.6000	0.0200	62.6000	50.0000
8.5000	0.9997	151.4000	0.0245	61.4000	50.0000
9.0000	0.9996	150.4500	0.0282	60.4500	50.0000
9.5000	0.9994	148.9000	0.0346	58.9000	50.0000
10.0000	0.9991	147.8000	0.0424	57.8000	50.0000
10.5000	0.9984	144.9141	0.0564	54.9141	50.0000
11.0000	0.9973	141.2859	0.0741	51.2859	50.0000
11.5000	0.9951	136.8141	0.0990	46.8141	50.0000
12.0000	0.9906	130.9922	0.1370	40.9922	50.0000

Table 10. Touchstone data file containing the computed scattering coefficients of an inductive strip of length T = 20 mils centered in WR(90) fin-line, W/b = 0.5.

```
! SCATTERING PARAMETERS:

! FREQ /S11/   <S11      /S21/    <S21      /S12/    <S12      /S22/    <S22

8.0    .8918  150.0188  .4525   60.0188   .4525   60.0188   .8918   150.0188
8.5    .8576  145.6312  .5143   55.6312   .5143   55.6312   .8576   145.6312
9.0    .8217  141.4125  .5700   51.4125   .5700   51.4125   .8217   141.4125
9.5    .7852  137.8969  .6193   47.8969   .6193   47.8969   .7852   137.8969
10.0   .7508  133.8047  .6506   43.8047   .6606   43.8047   .7508   133.8047
10.5   .7140  131.1328  .7001   41.1328   .7001   41.1328   .7140   131.1328
11.0   .6799  127.8141  .7333   37.8141   .7333   37.8141   .6799   127.8141
11.5   .6451  125.9875  .7641   35.9875   .7641   35.9875   .6451   125.9875
12.0   .6150  121.8100  .7940   31.8100   .7940   31.8100   .6150   121.8100
```

Table 11. Touchstone data file containing the computed scattering coefficients of an inductive strip of length T = 50 mils centered in WR(90) fin-line, W/b = 0.5.

```
! SCATTERING PARAMETERS:

! FREQ /S11/     <S11      /S21/     <S21       /S12/    <S12       /S22/     <S22

8.0    .9591    157.0078  .2832     67.0078    .2832    67.0078    .9591    157.0078
8.5    .9476    153.5625  .3195     63.5625    .3195    63.5625    .9476    153.5625
9.0    .9347    150.9609  .3553     60.9609    .3553    60.9609    .9347    150.9609
9.5    .9202    148.1344  .3915     58.1344    .3915    58.1344    .9202    148.1344
10.0   .9035    145.1250  .4287     55.1250    .4287    55.1250    .9035    145.1250
10.5   .8855    141.8062  .4647     51.8062    .4647    51.8062    .8855    141.8062
11.0   .8648    139.1906  .5021     49.1906    .5021    49.1906    .8648    139.1906
11.5   .8423    135.6187  .5389     45.6187    .5389    45.6187    .8423    135.6187
12.0   .8174    132.5531  .5760     42.5531    .5760    42.5531    .8174    132.5531
```

Table 12. Touchstone data file containing the computed scattering coefficients of an inductive strip of length T = 200 mils centered in WR(90) fin-line, W/b = 0.5.

```
! SCATTERING PARAMETERS:

! FREQ /S11/    <S11      /S21/     <S21      /S12/     <S12      /S22/     <S22

8.0    .9314   155.5734  .3640    65.5734   .3640    65.5734   .9314    155.5734
8.5    .9134   152.0578  .4070    62.0578   .4070    62.0578   .9134    152.0578
9.0    .8938   149.3438  .4485    59.3438   .4485    59.3438   .8938    149.3438
9.5    .8720   146.5172  .4895    56.5172   .4895    56.5172   .8720    146.5172
10.0   .8494   143.7188  .5277    53.7188   .5277    53.7188   .8494    143.7188
10.5   .8256   140.4563  .5643    50.4563   .5643    50.4563   .8256    140.4563
11.0   .7992   138.1219  .6010    48.1219   .6010    48.1219   .7992    138.1219
11.5   .7725   134.9719  .6350    44.9719   .6350    44.9719   .7725    134.9719
12.0   .7447   132.3562  .6674    42.3562   .6674    42.3562   .7447    132.3562
```

Table 13. Touchstone data file containing the computed scattering coefficients of an inductive strip of length T = 500 mils centered in WR(90) fin-line, W/b = 0.5.

```
! SCATTERING PARAMETERS:

! FREQ /S11/   <S11     /S21/   <S21     /S12/   <S12     /S22/   <S22

8.0   .9999  150.3000  .0255   60.3000  .0255   60.3000  .9999   150.3000
8.5   .9995  148.4437  .0355   58.4437  .0355   58.4437  .9995   149.4437
9.0   .9989  146.5875  .0464   56.5875  .0464   56.5875  .9989   146.5875
9.5   .9984  142.7625  .0557   52.7625  .0557   52.7625  .9984   142.7625
10.0  .9975  137.5875  .0709   47.5875  .0709   47.5875  .9975   137.5875
10.5  .9960  133.3125  .0995   43.3125  .0895   43.3125  .9960   133.3125
11.0  .9934  127.6172  .1151   37.6172  .1151   37.6172  .9934   127.6172
11.5  .9887  121.6266  .1501   31.6266  .1501   31.6166  .9987   121.6266
12.0  .9802  113.8641  .1980   23.8641  .1980   23.8641  .9802   113.8641
```

Table 14. Touchstone data file containing the computed scattering coefficients of an inductive strip of length T=20 mils centered in WR(90) fin-line, W/b=0.25.

```
! SCATTERING PARAMETERS:

! FREQ /S11/    <S11      /S21/     <S21       /S12/    <S12      /S22/     <S22

8.0    .9314   155.5734  .3640     65.5734   .3640    65.5734   .9314   155.5734
8.5    .9134   152.0578  .4070     62.0578   .4070    62.0578   .9134   152.0578
9.0    .8938   149.3438  .4485     59.3438   .4485    59.3438   .8938   149.3438
9.5    .8720   146.5172  .4895     56.5172   .4895    56.5172   .8720   146.5172
10.0   .8494   143.7188  .5277     53.7188   .5277    53.7188   .8494   143.7188
10.5   .8256   140.4563  .5643     50.4563   .5643    50.4563   .8256   140.4563
11.0   .7992   138.1219  .6010     48.1219   .6010    48.1219   .7992   138.1219
11.5   .7725   134.9719  .6350     44.9719   .6350    44.9719   .7725   134.9719
12.0   .7447   132.3562  .6674     42.3562   .6674    42.3562   .7447   132.3562
```

Table 15. Touchstone data file containing the computed scattering coefficients of an inductive strip of length T = 50 mils centered in WR(90) fin-line, W/b = 0.25.

```
! SCATTERING PARAMETERS:

! FREQ /S11/    <S11      /S21/     <S21       /S12/    <S12       /S22/    <S22

8.0     .9591    157.0078  .2832     67.0078    .2832    67.0078    .9591    157.0078
8.5     .9476    153.5625  .3195     63.5625    .3195    63.5625    .9476    153.5625
9.0     .9347    150.9609  .3553     60.9609    .3553    60.9609    .9347    150.9609
9.5     .9202    148.1344  .3915     58.1344    .3915    58.1344    .9202    148.1344
10.0    .9035    145.1250  .4287     55.1250    .4287    55.1250    .9035    145.1250
10.5    .8855    141.8062  .4647     51.8062    .4647    51.8062    .8855    141.8062
11.0    .8648    139.1906  .5021     49.1906    .5021    49.1906    .8648    139.1906
11.5    .8423    135.6187  .5389     45.6187    .5389    45.6187    .8423    135.6187
12.0    .8174    132.5531  .5760     42.5531    .5760    42.5531    .8174    132.5531
```

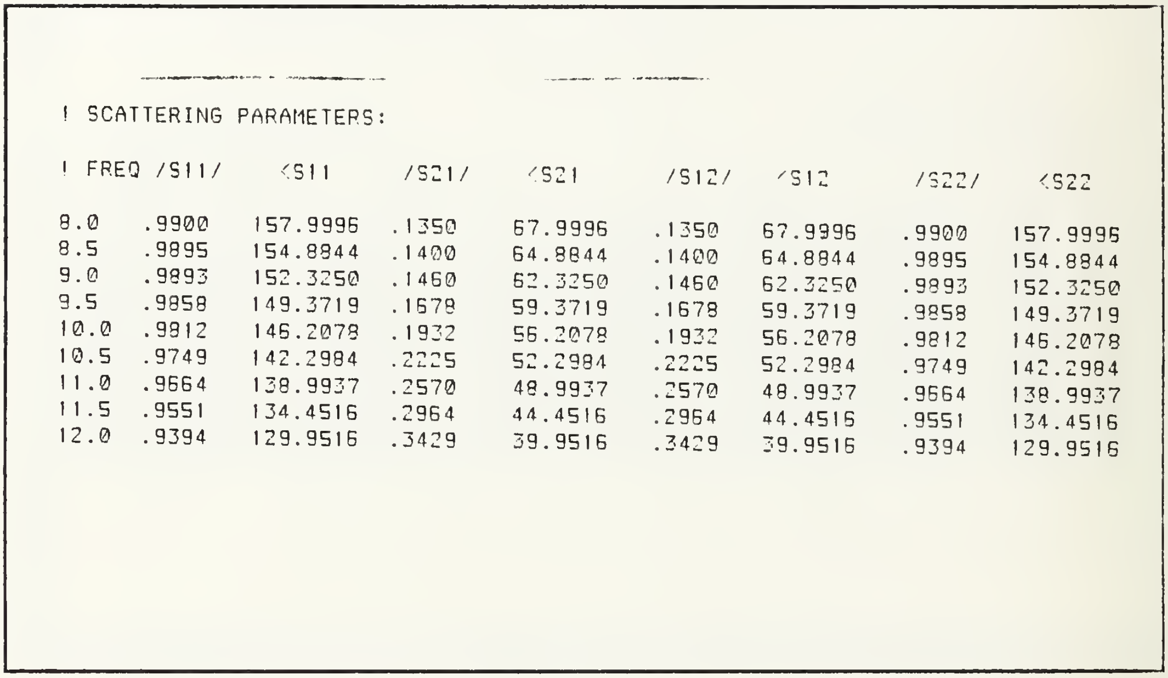
Table 16. Touchstone data file containing the computed scattering coefficients of an inductive strip of length T = 100 mils centered in WR(90) fin-line, W/b = 0.25.

```
! SCATTERING PARAMETERS:

! FREQ /S11/    <S11      /S21/    <S21      /S12/   <S12      /S22/    <S22

8.0   .9755   156.6281  .2198    66.6281   .2198   66.6281   .9755   156.6281
8.5   .9739   154.5188  .2270    64.5188   .2270   64.5188   .9739   154.5188
9.0   .9667   151.8750  .2561    61.8750   .2561   61.8750   .9667   151.8750
9.5   .9577   149.9781  .2877    58.9781   .2877   59.9781   .9577   148.9781
10.0  .9472   145.8984  .3207    55.8984   .3207   55.8984   .9472   145.8984
10.5  .9351   142.3266  .3544    52.3266   .3544   52.3266   .9351   142.3266
11.0  .9201   139.4297  .3917    49.4297   .3917   49.4297   .9201   139.4297
11.5  .9023   135.4359  .4311    45.4359   .4311   45.4359   .9023   135.4359
12.0  .8808   131.6953  .4736    41.6953   .4736   41.6953   .8808   131.6953
```

Table 17. Touchstone data file containing the computed scattering coefficients of an inductive strip of length T = 200 mils centered in WR(90) fin-line, W/b = 0.25.



```
! SCATTERING PARAMETERS:

! FREQ /S11/    <S11      /S21/    <S21      /S12/   <S12      /S22/   <S22

8.0    .9900   157.9996  .1350    67.9996   .1350   67.9996   .9900   157.9996
8.5    .9895   154.8844  .1400    64.8844   .1400   64.8844   .9895   154.8844
9.0    .9893   152.3250  .1460    62.3250   .1460   62.3250   .9893   152.3250
9.5    .9858   149.3719  .1678    59.3719   .1678   59.3719   .9858   149.3719
10.0   .9812   146.2078  .1932    56.2078   .1932   56.2078   .9812   146.2078
10.5   .9749   142.2984  .2225    52.2984   .2225   52.2984   .9749   142.2984
11.0   .9664   138.9937  .2570    48.9937   .2570   48.9937   .9664   138.9937
11.5   .9551   134.4516  .2964    44.4516   .2964   44.4516   .9551   134.4516
12.0   .9394   129.9516  .3429    39.9516   .3429   39.9516   .9394   129.9516
```

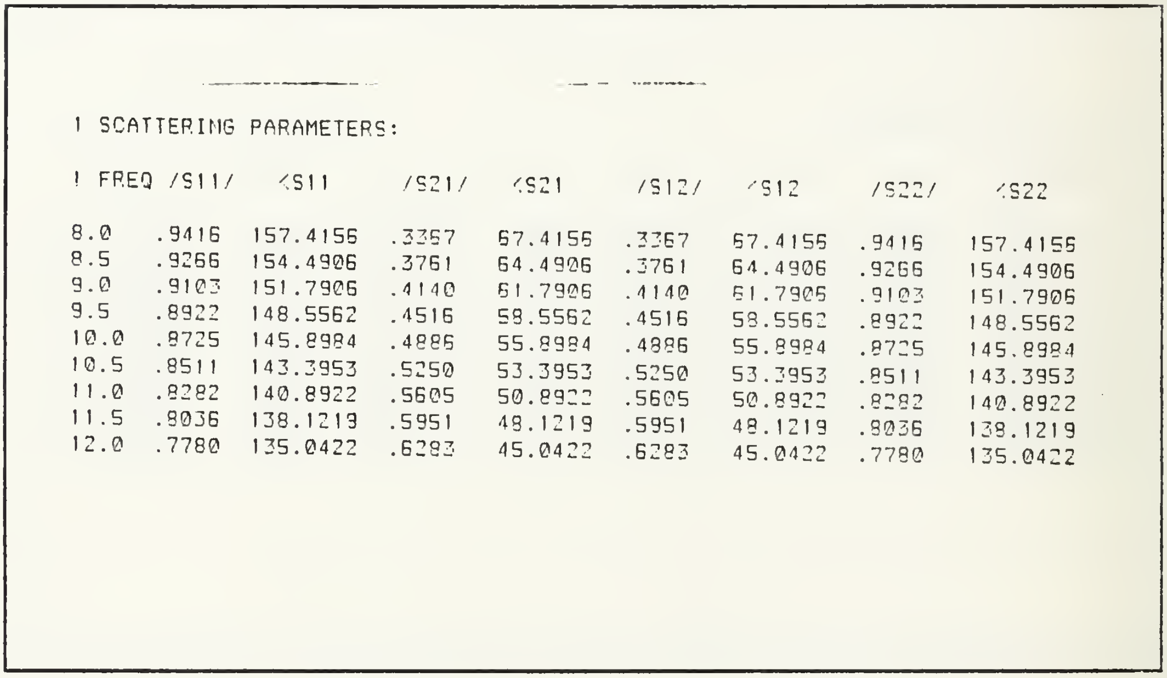
Table 18. Touchstone data file containing the computed scattering coefficients of an inductive strip of length T = 500 mils centered in WR(90) fin-line, W/b = 0.25.

```
! SCATTERING PARAMETERS:

! FREQ /S11/    <S11      /S21/     <S21       /S12/    <S12       /S22/    <S22

8.0   .9999   153.3987  .0141    63.3987    .0141    63.3987    .9999   153.3987
8.5   .9998   152.5325  .0190    62.5325    .0190    62.5325    .9999   152.5325
9.0   .9996   150.8792  .0283    60.8792    .0283    60.8792    .9996   150.8792
9.5   .9994   149.5991  .0346    58.5981    .0346    58.5991    .9994   149.5981
10.0  .9988   146.1797  .0491    56.1797    .0491    56.1797    .9988   146.1797
10.5  .9980   142.1859  .0628    52.1859    .0629    52.1859    .9980   142.1859
11.0  .9956   138.5297  .0824    48.5297    .0824    48.5297    .9966   138.5297
11.5  .9941   133.2984  .1088    43.2984    .1089    43.2984    .1089   133.2984
12.0  .9889   127.7156  .1494    37.7156    .1484    37.7156    .9889   127.7156
```

Table 19. Touchstone data file containing the computed scattering coefficients of an inductive strip of length T = 20 mils centered in WR(90) fin-line, W/b = 0.2.



```
! SCATTERING PARAMETERS:

! FREQ /S11/   <S11      /S21/   <S21      /S12/   <S12      /S22/   <S22

8.0   .9416  157.4156  .3367   67.4156  .3367   67.4156  .9416  157.4156
8.5   .9266  154.4906  .3761   64.4906  .3761   64.4906  .9266  154.4906
9.0   .9103  151.7906  .4140   61.7906  .4140   61.7905  .9103  151.7906
9.5   .8922  148.5562  .4516   58.5562  .4516   58.5562  .8922  148.5562
10.0  .8725  145.8984  .4886   55.8984  .4886   55.8984  .8725  145.8984
10.5  .8511  143.3953  .5250   53.3953  .5250   53.3953  .8511  143.3953
11.0  .8282  140.8922  .5605   50.8922  .5605   50.8922  .8282  140.8922
11.5  .8036  138.1219  .5951   48.1219  .5951   48.1219  .8036  138.1219
12.0  .7780  135.0422  .6283   45.0422  .6283   45.0422  .7780  135.0422
```

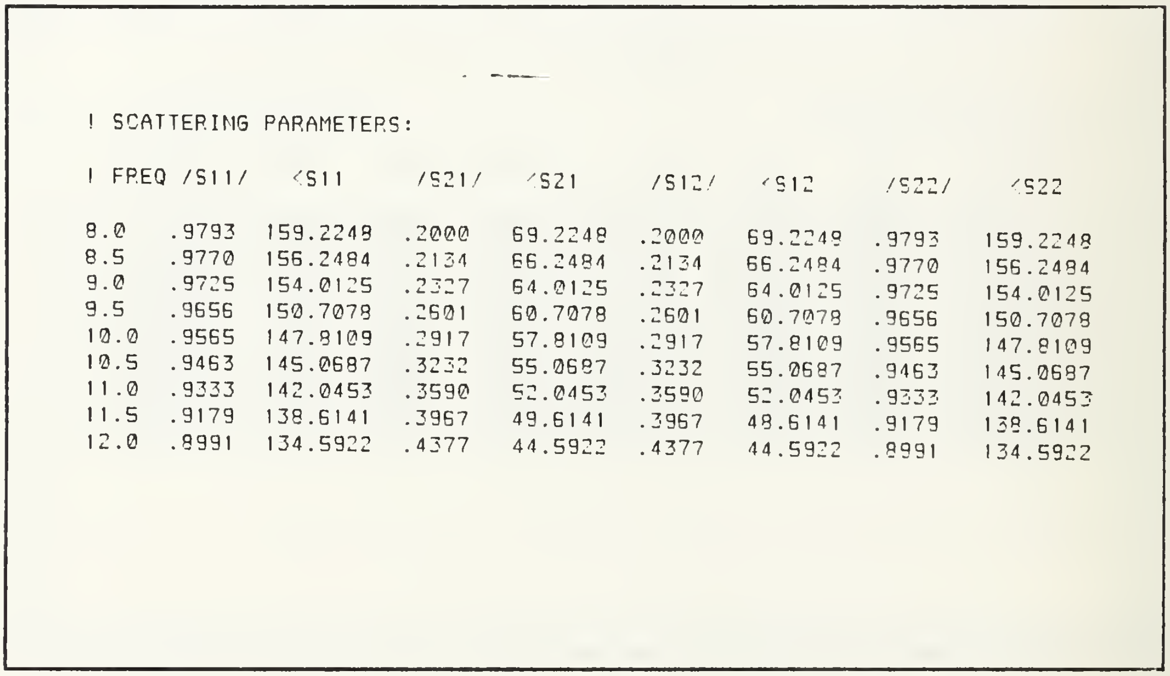
Table 20. Touchstone data file containing the computed scattering coefficients of an inductive strip of length T = 50 mils centered in WR(90) fin-line, W/b = 0.2.

```
! SCATTERING PARAMETERS:

! FREQ  /S11/    <S11      /S21/    <S21       /S12/    <S12       /S22/    <S22

8.0     .9653   158.6531  .2613    68.6531   .2613    68.6513   .9653   159.6531
8.5     .9559   155.7984  .2936    65.7994   .2936    65.7984   .9559   155.7984
9.0     .9456   153.2109  .3253    63.2109   .3253    63.2109   .9456   153.2109
9.5     .9336   150.0188  .3583    60.0189   .3593    60.0188   .9336   150.0188
10.0    .9197   147.2203  .3926    57.2203   .3926    57.2203   .9197   147.2203
10.5    .9041   144.6187  .4273    54.6187   .4273    54.6187   .9041   144.6187
11.0    .8861   141.8766  .4636    51.8766   .4636    51.8766   .8861   141.8766
11.5    .8658   138.7969  .5004    48.7969   .5004    48.7959   .8658   138.7969
12.0    .8437   135.3375  .5369    45.3375   .5369    45.3375   .8437   135.3375
```

Table 21. Touchstone data file containing the computed scattering coefficients of an inductive strip of length T = 100 mils centered in WR(90) fin-line, W/b = 0.2.

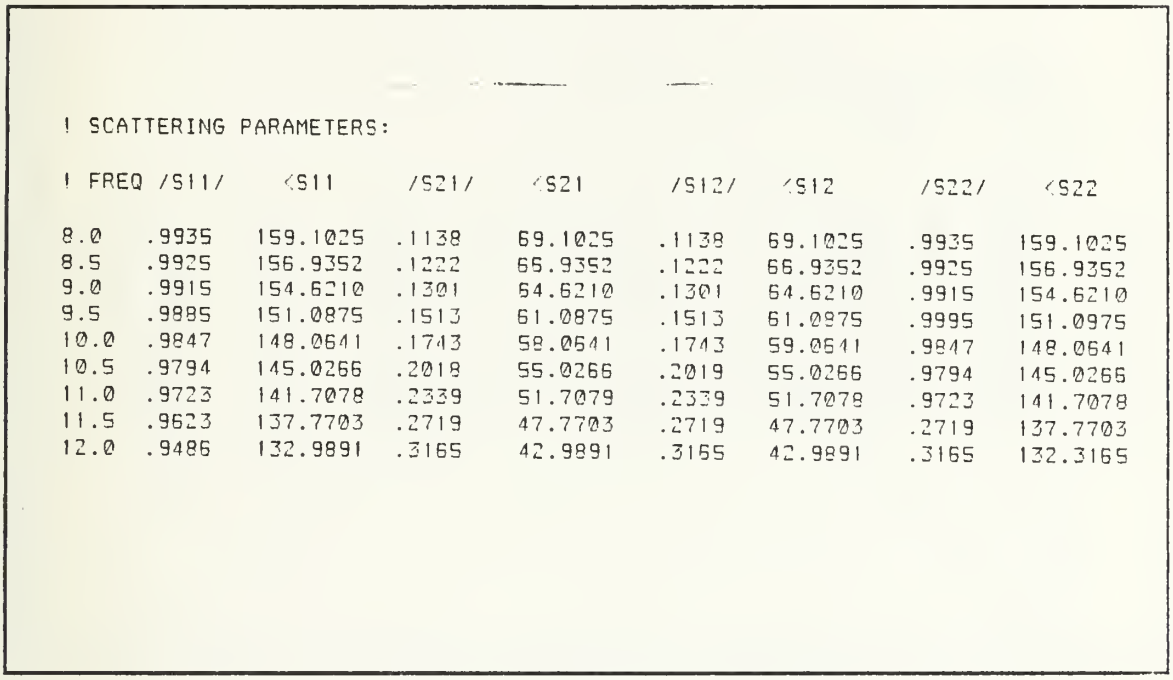


```
! SCATTERING PARAMETERS:

! FREQ /S11/   <S11      /S21/   <S21      /S12/   <S12      /S22/    <S22

8.0   .9793  159.2248  .2000   69.2248  .2000   69.2248  .9793   159.2248
8.5   .9770  156.2484  .2134   66.2484  .2134   66.2484  .9770   156.2484
9.0   .9725  154.0125  .2327   64.0125  .2327   64.0125  .9725   154.0125
9.5   .9656  150.7078  .2601   60.7078  .2601   60.7078  .9656   150.7078
10.0  .9565  147.8109  .2917   57.8109  .2917   57.8109  .9565   147.8109
10.5  .9463  145.0687  .3232   55.0687  .3232   55.0687  .9463   145.0687
11.0  .9333  142.0453  .3590   52.0453  .3590   52.0453  .9333   142.0453
11.5  .9179  138.6141  .3967   49.6141  .3967   48.6141  .9179   138.6141
12.0  .8991  134.5922  .4377   44.5922  .4377   44.5922  .8991   134.5922
```

Table 22. Touchstone data file containing the computed scattering coefficients of an inductive strip of length T = 200 mils centered in WR(90) fin-line, W/b = 0.2.



```
! SCATTERING PARAMETERS:

! FREQ /S11/    <S11     /S21/    <S21      /S12/    <S12      /S22/    <S22

8.0   .9935   159.1025  .1138    69.1025   .1138   69.1025   .9935   159.1025
8.5   .9925   156.9352  .1222    66.9352   .1222   66.9352   .9925   156.9352
9.0   .9915   154.6210  .1301    64.6210   .1301   64.6210   .9915   154.6210
9.5   .9885   151.0875  .1513    61.0875   .1513   61.0975   .9995   151.0975
10.0  .9847   148.0641  .1743    58.0641   .1743   59.0641   .9847   148.0641
10.5  .9794   145.0266  .2018    55.0266   .2019   55.0266   .9794   145.0266
11.0  .9723   141.7078  .2339    51.7079   .2339   51.7078   .9723   141.7078
11.5  .9623   137.7703  .2719    47.7703   .2719   47.7703   .2719   137.7703
12.0  .9486   132.9891  .3165    42.9891   .3165   42.9891   .3165   132.3165
```

Table 23. Touchstone data file containing the computed scattering coefficients of an inductive strip of length T = 500 mils centered in WR(90) fin-line, W/b = 0.2.

```
! SCATTERING PARAMETERS:

! FREQ /S11/    <S11       /S21/    <S21       /S12/    <S12       /S22/    <S22

8.0    .9998    152.6000   .0200    62.6000    .0200    62.6000    .9998    152.6000
8.5    .9997    151.4000   .0245    61.4000    .0245    61.4000    .9997    151.4000
9.0    .9996    150.4500   .0282    60.4500    .0282    60.4500    .9996    150.4500
9.5    .9994    148.9000   .0346    58.9000    .0346    58.9000    .9994    148.9000
10.0   .9991    147.8000   .0424    57.8000    .0424    57.8000    .9991    147.8000
10.5   .9984    144.9141   .0564    54.9141    .0564    54.9141    .9984    144.9141
11.0   .9973    141.2859   .0741    51.2859    .0741    51.2859    .9973    141.2859
11.5   .9951    136.8141   .0990    46.8141    .0990    46.8141    .9951    136.8141
12.0   .9906    130.9922   .1370    40.9922    .1370    40.9922    .9906    130.9922
```

APPENDIX B. SUPPORTIVE FIGURES

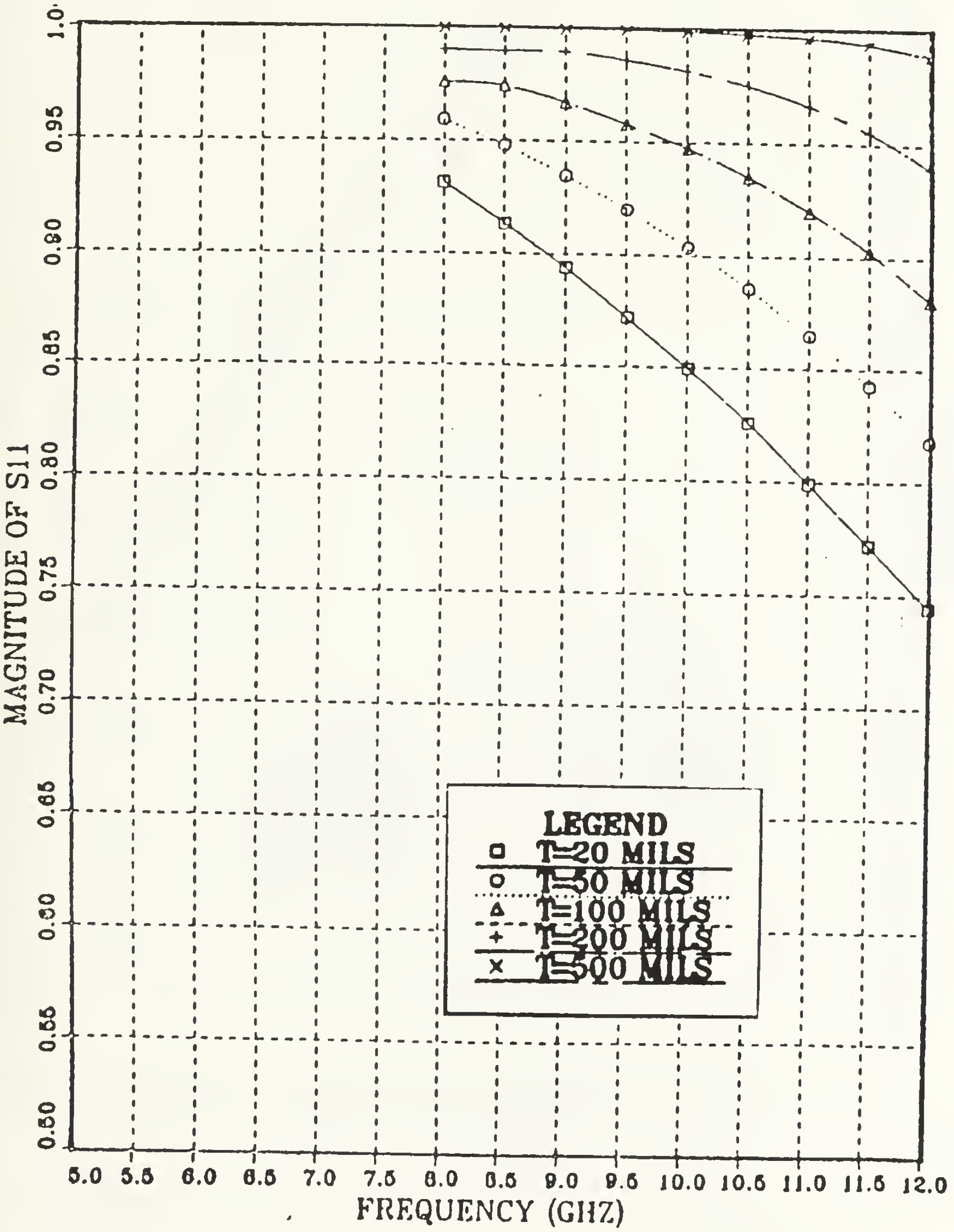


Figure 18. $|S_{11}|$ vs. frequency for inductive strips centered in WR(90) fin-line. W/b = 0.25, E_{r2} = 1.

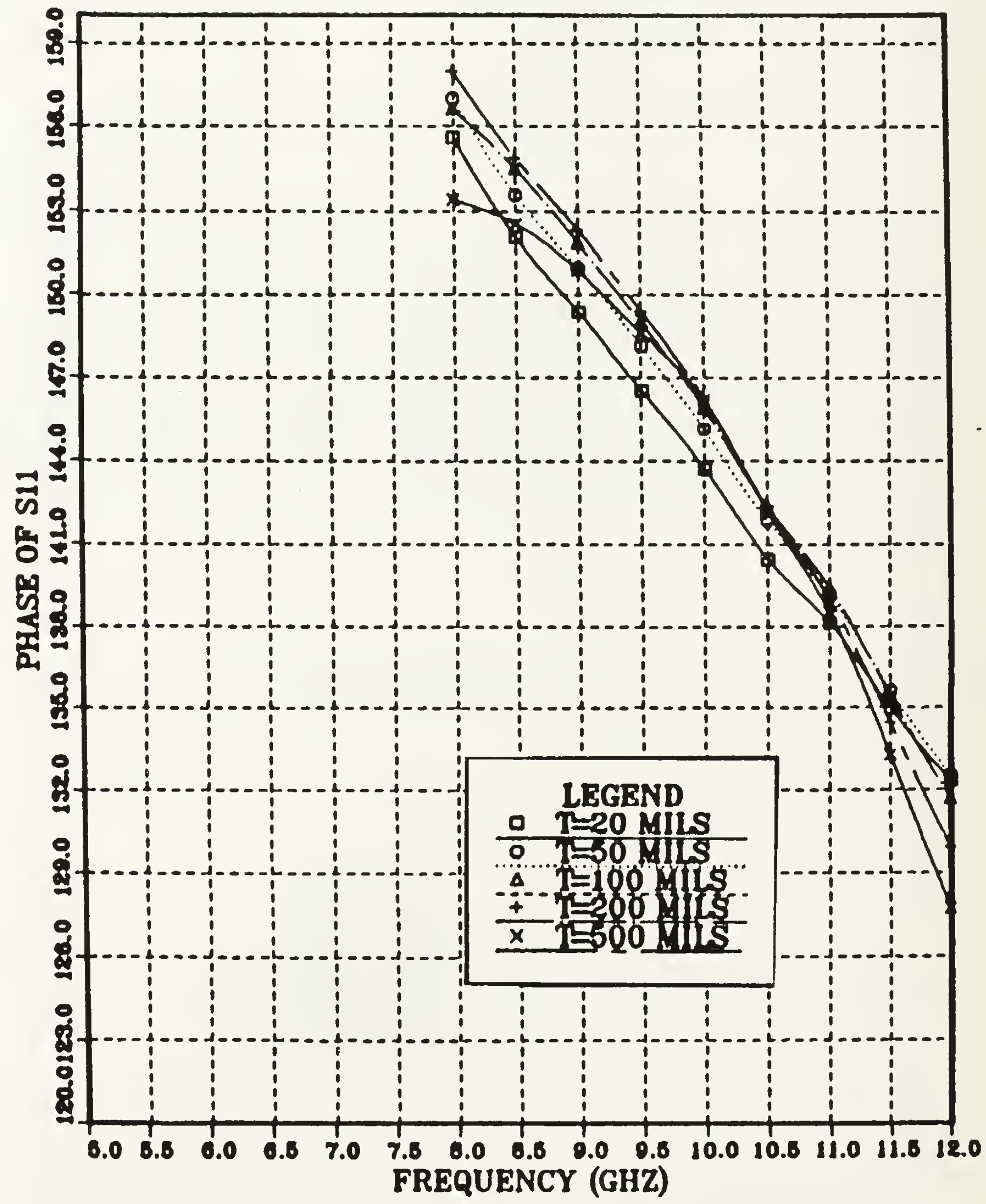


Figure 19. θ_{11} vs. frequency for inductive strips centered in WR(90) fin-line. W/b = 0.25, $E_{r2} = 1$.

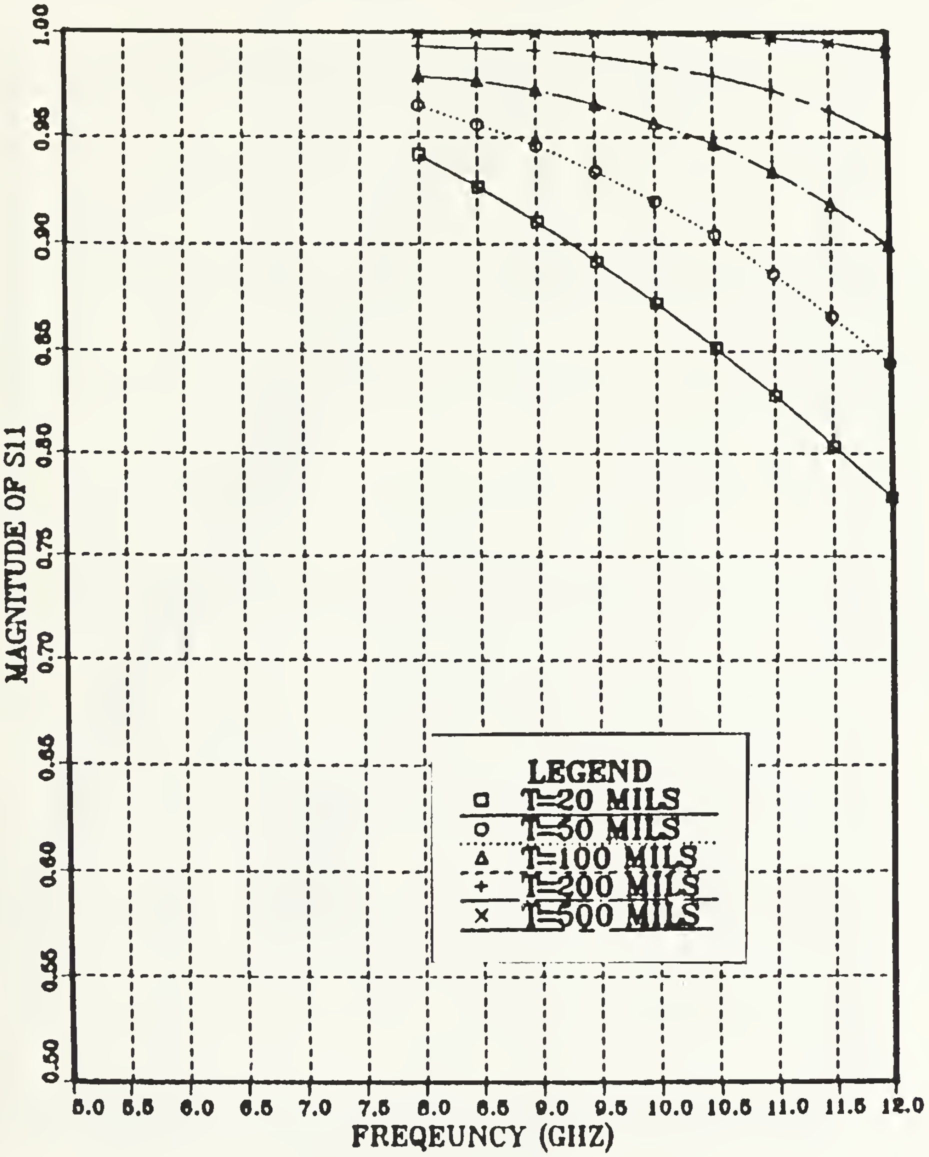


Figure 20. $|S_{11}|$ vs. frequency for inductive strips centered in Wr(90) fin-line. $W/b = 0.2$, $E_{r2} = 1$.

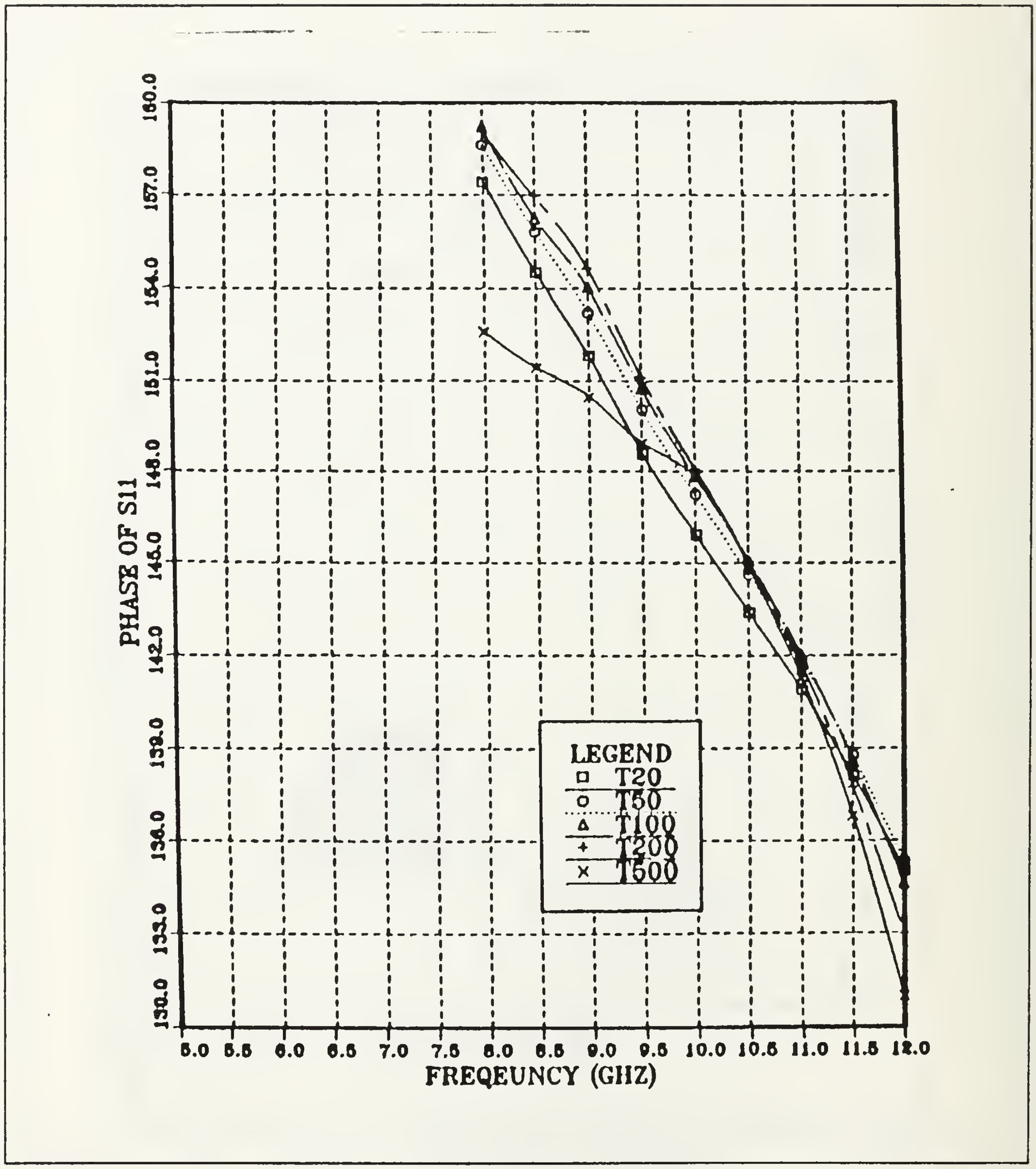


Figure 21. θ_{11} vs. frequency for inductive strips centered in WR(90) fin-line. W/b = o.2, $E_{r2} = 1$.

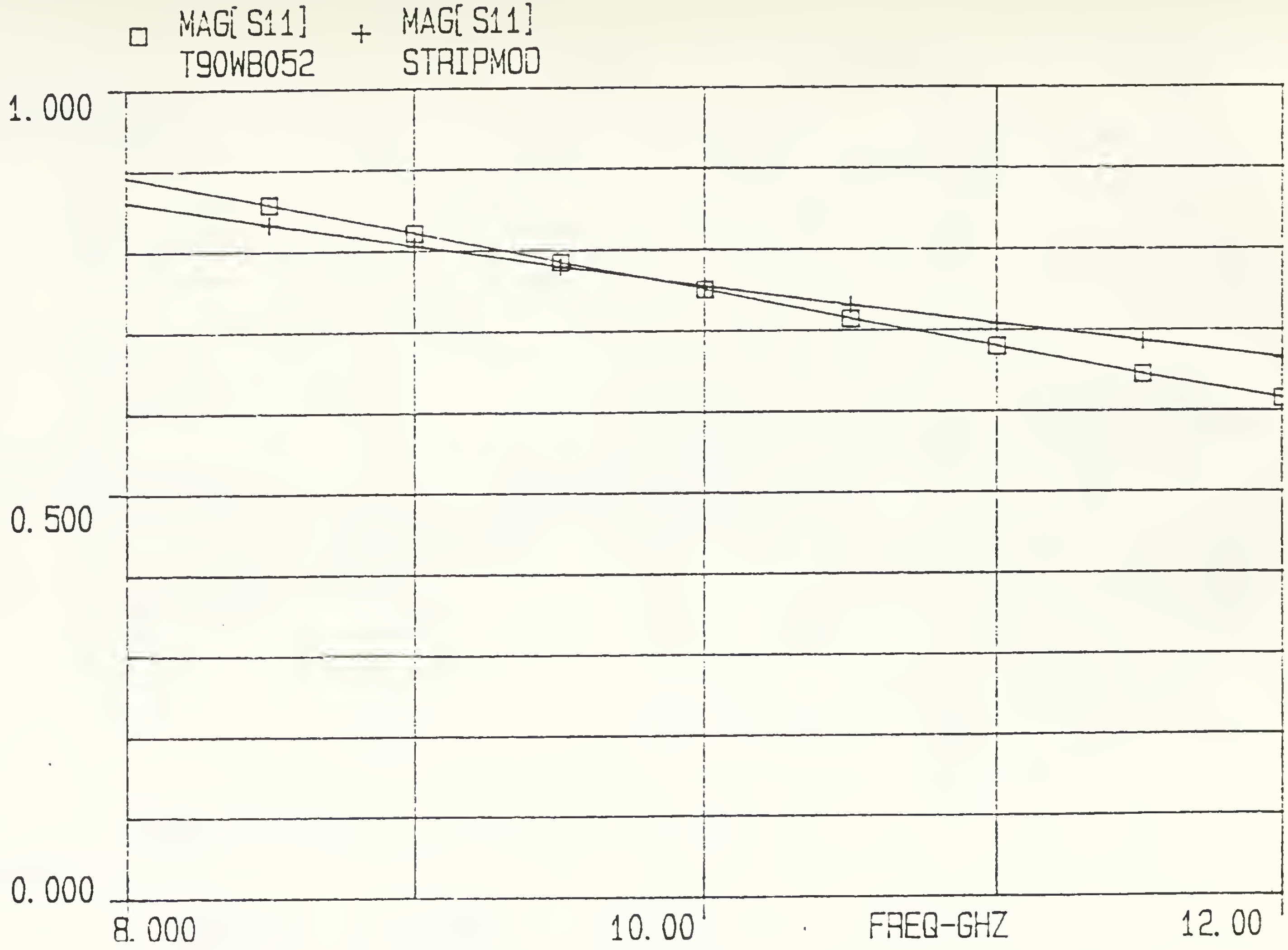


Figure 22. Computed and predicted values of $|S_{11}|$ vs. frequency for a T = 20 mils inductive strip centered in WR(90) fin-line, W/b = 0.5, $E_{r2} = 1$. Model inductance L = 10.7 nH.

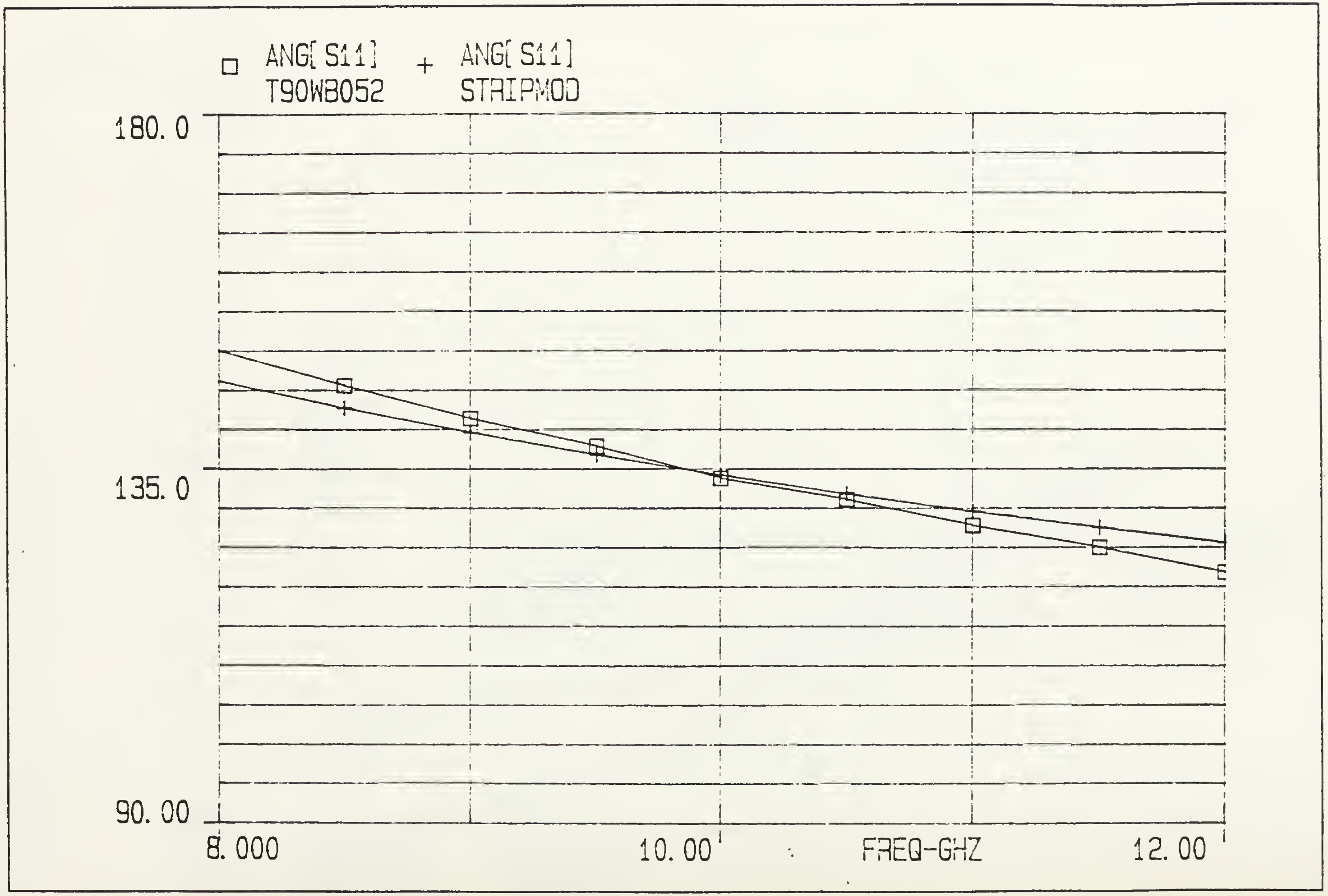


Figure 23. Computed and predicted values of θ_{11} vs. frequency for a T = 20 mils inductive strip centered in WR(90) fin-line, **W/b = 0.5, E_{r2} = 1. Model inductance L = 10.7 nH.**

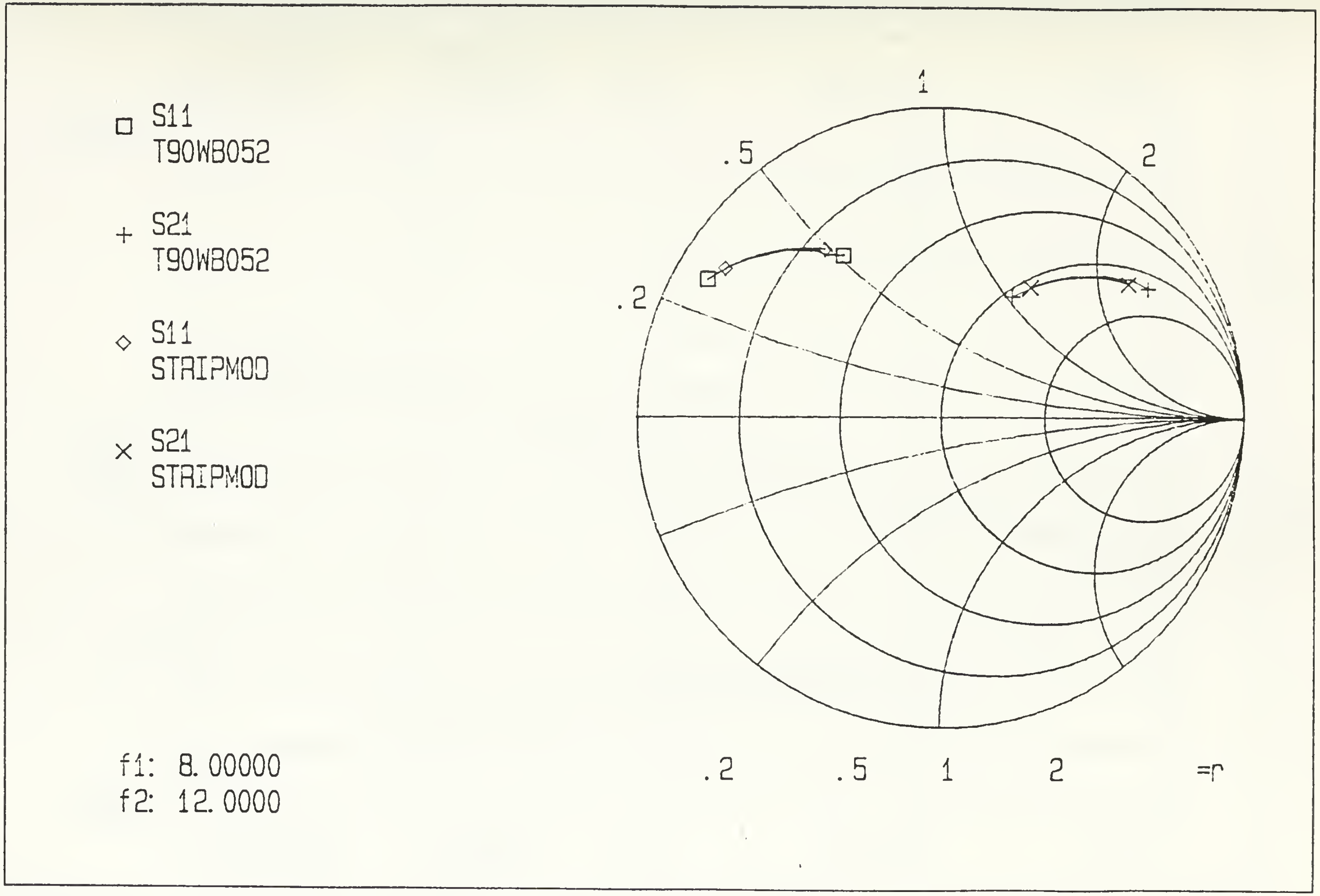


Figure 24. Smith chart plot of computed and predicted values of S_{11} and S21 for a T = 20 mils inductive strip centered in WR(90) fin-line, W/b = 0.5, E_{r2} = 1. Model inductance L = 10.7 nH.

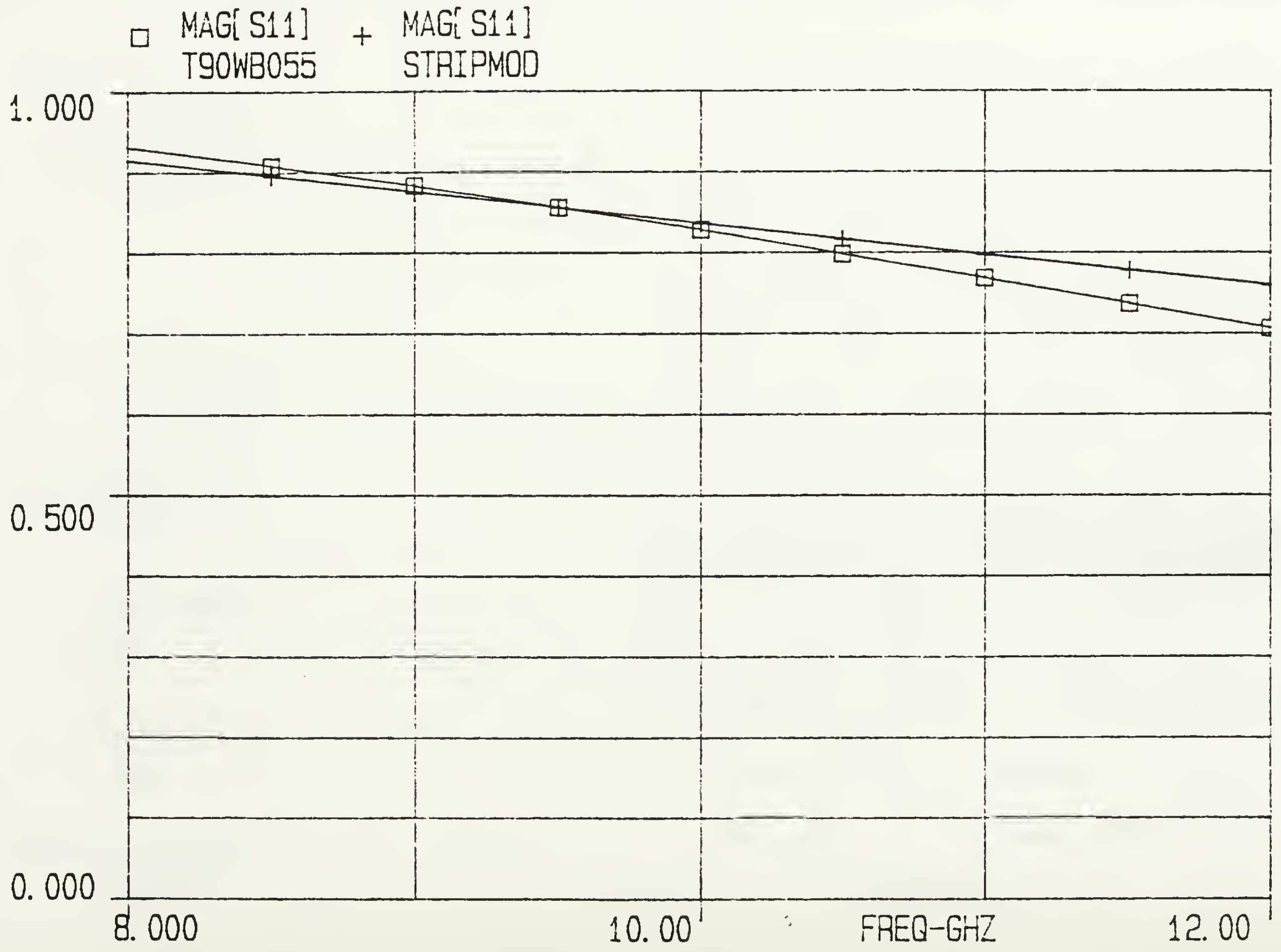


Figure 25. Computed and predicted values of $|S_{11}|$ vs. frequency for a T = 50 mils inductive strip centered in WR(90) finline, W/b = 0.5, E_{r2} = 1. Model inductance L = 9.35 nH.

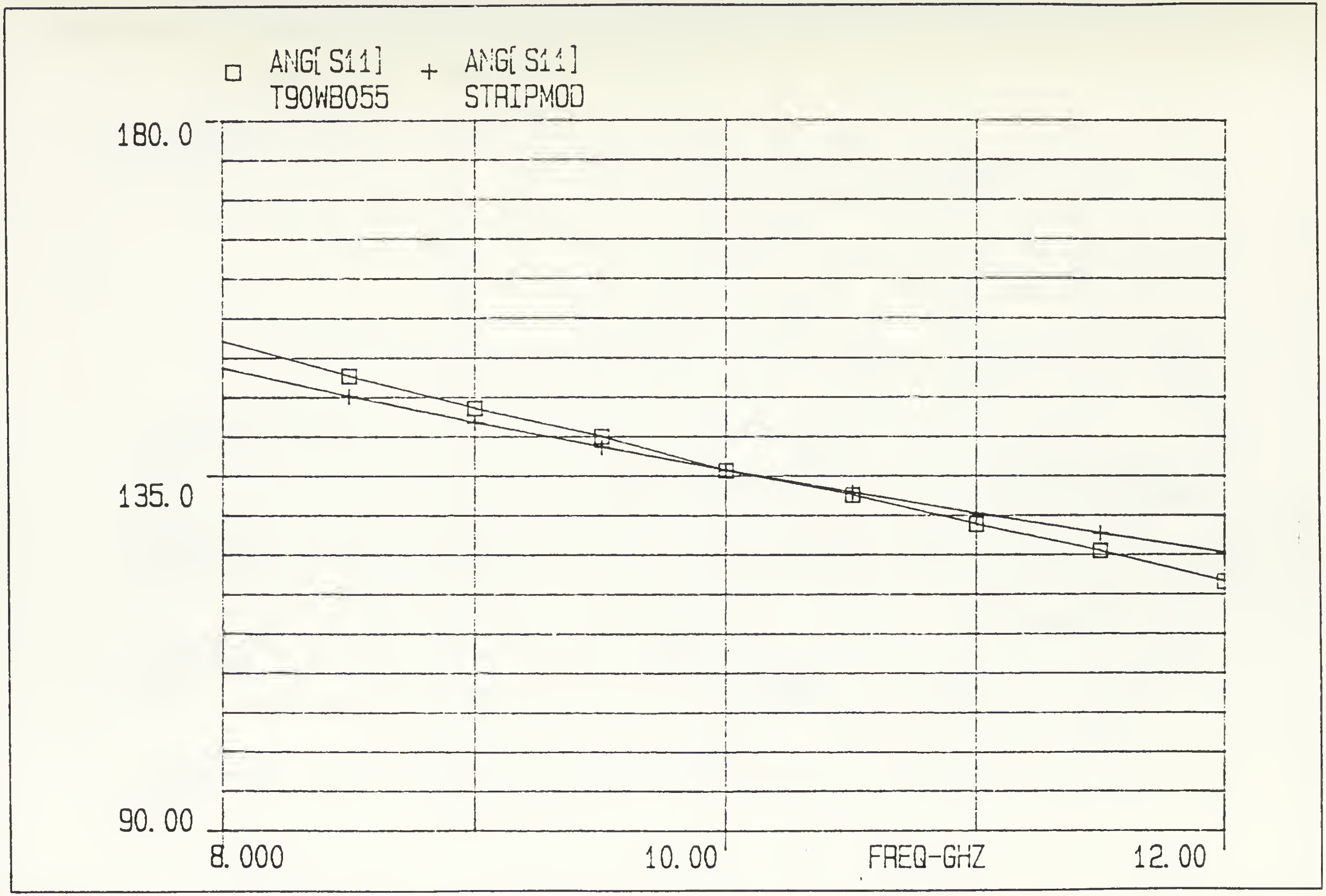


Figure 26. Computed and predicted values of θ_{11} vs. frequency for a T = 50 mils inductive strip centered in WR(90) fin-line, **W/b = 0.5, E_{r2} = 1. Model inductance L = 9.35 nH.**

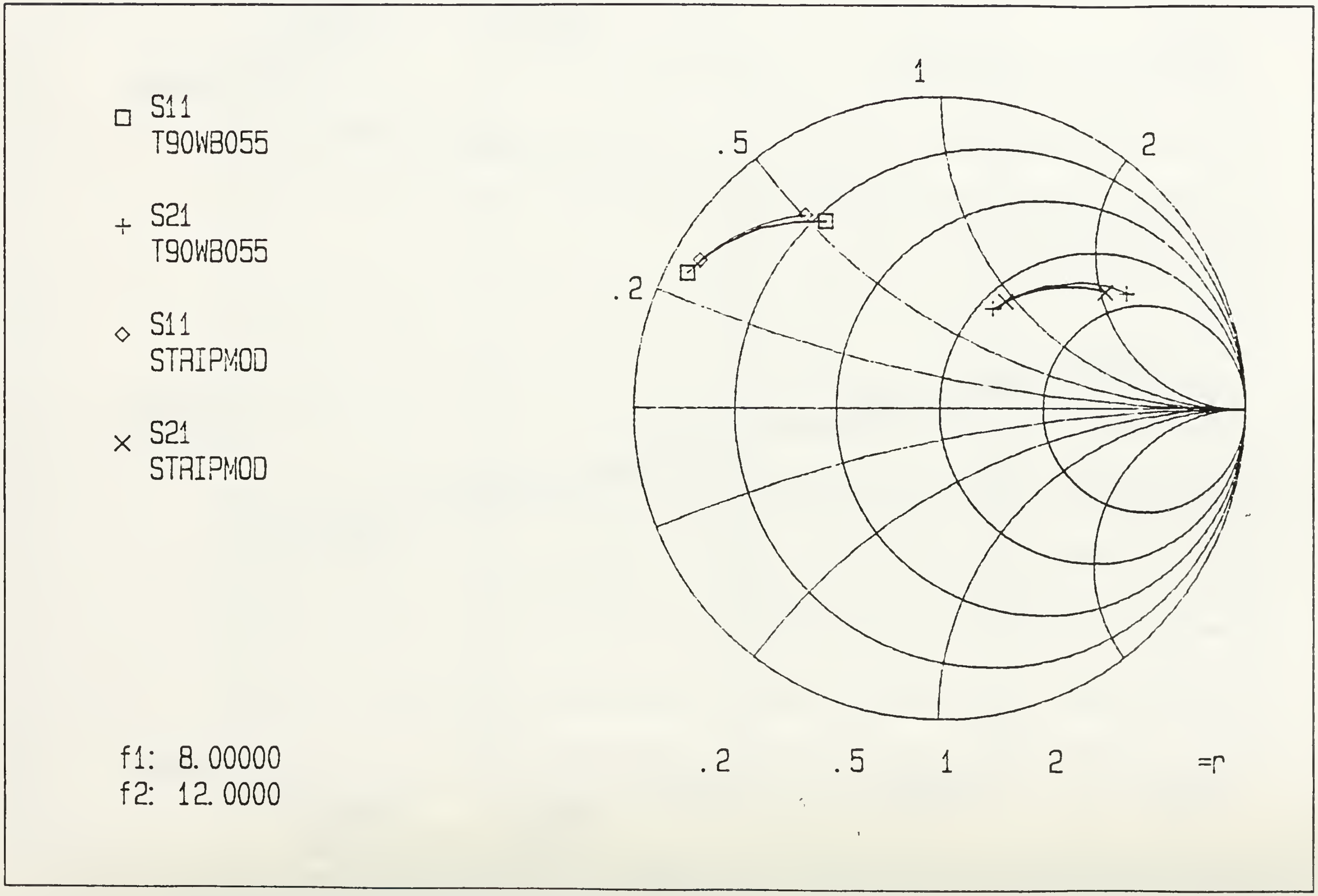


Figure 27. Smith chart plot of computed and predicted values of S_{11} and S21 for a T = 50 mils inductive strip centered in WR(90) fin-line, W/b = 0.5, E_{r2} = 1. Model inductance L = 9.35 nH.

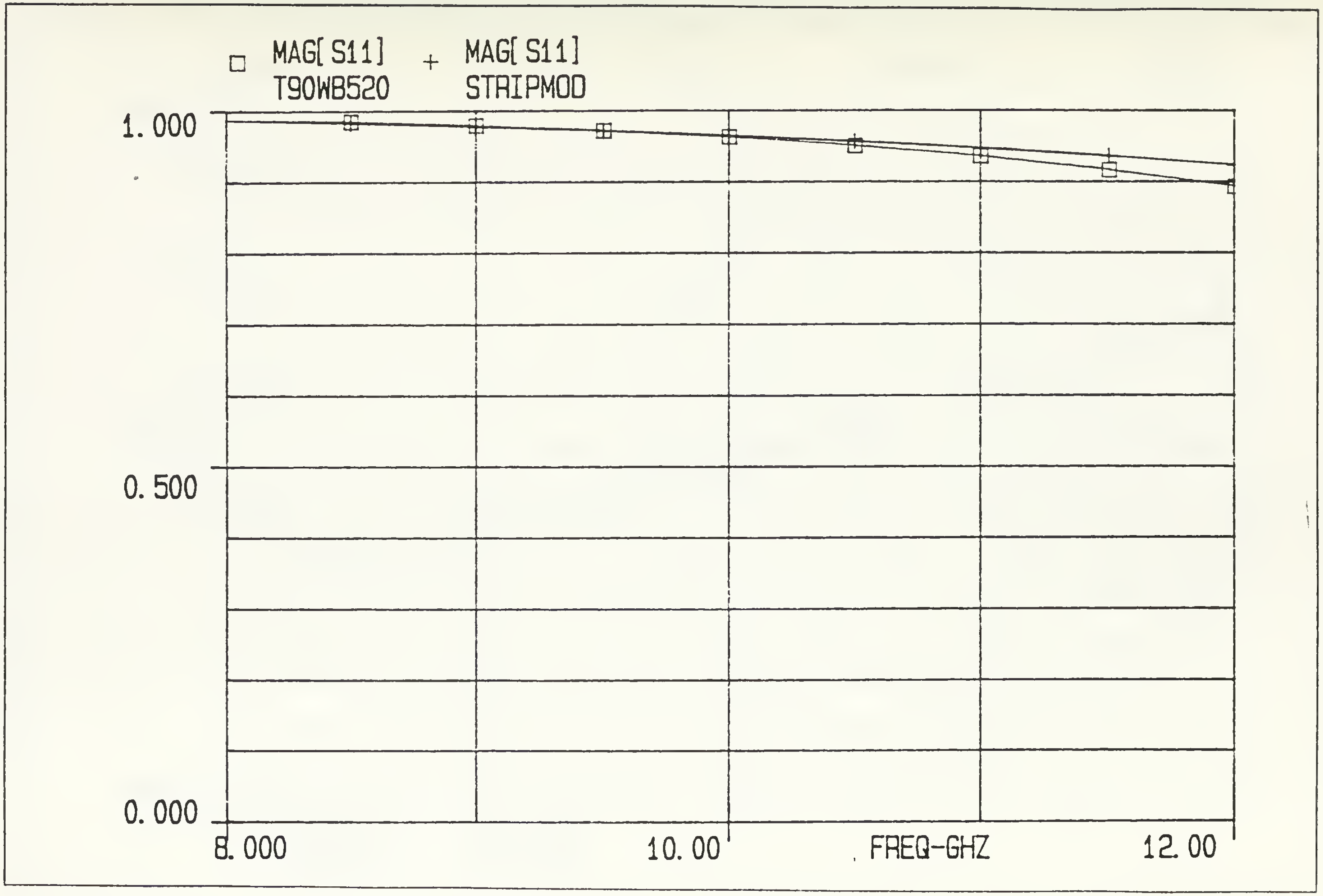


Figure 28. Computed and predicted values of $|S_{11}|$ vs. frequency for a T = 200 mils inductive strip centered in WR(90) fin-line, W/b = 0.5, E_{r2} = 1. Model inductance L = 7.10 nH.

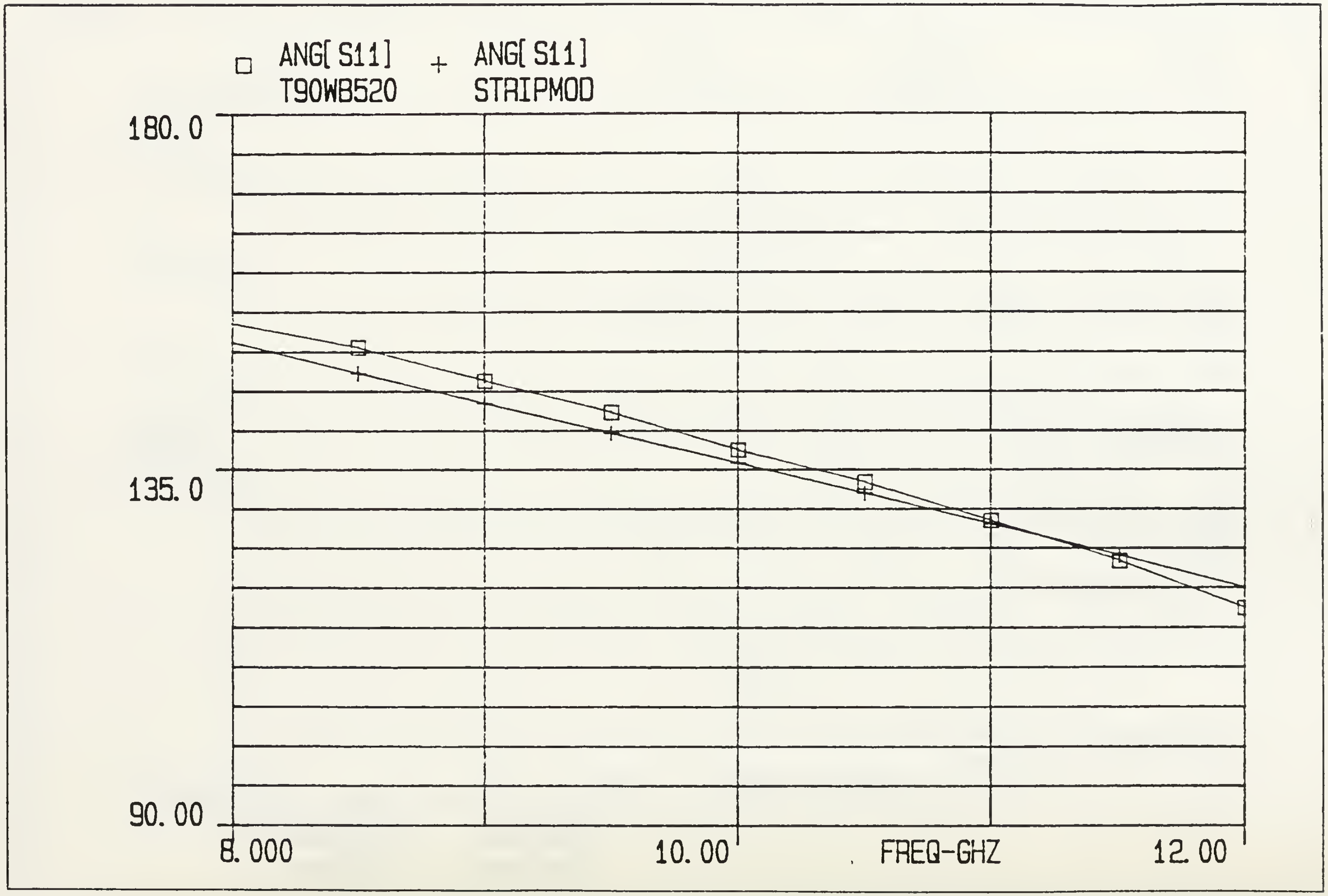


Figure 29. Computed and predicted values of θ_{11} vs. frequency for a T = 200 mils inductive strip centered in WR(90) fin-line, W/b = 0.5, E_{r2} = 1. Model inductance L = 7.10 nH.

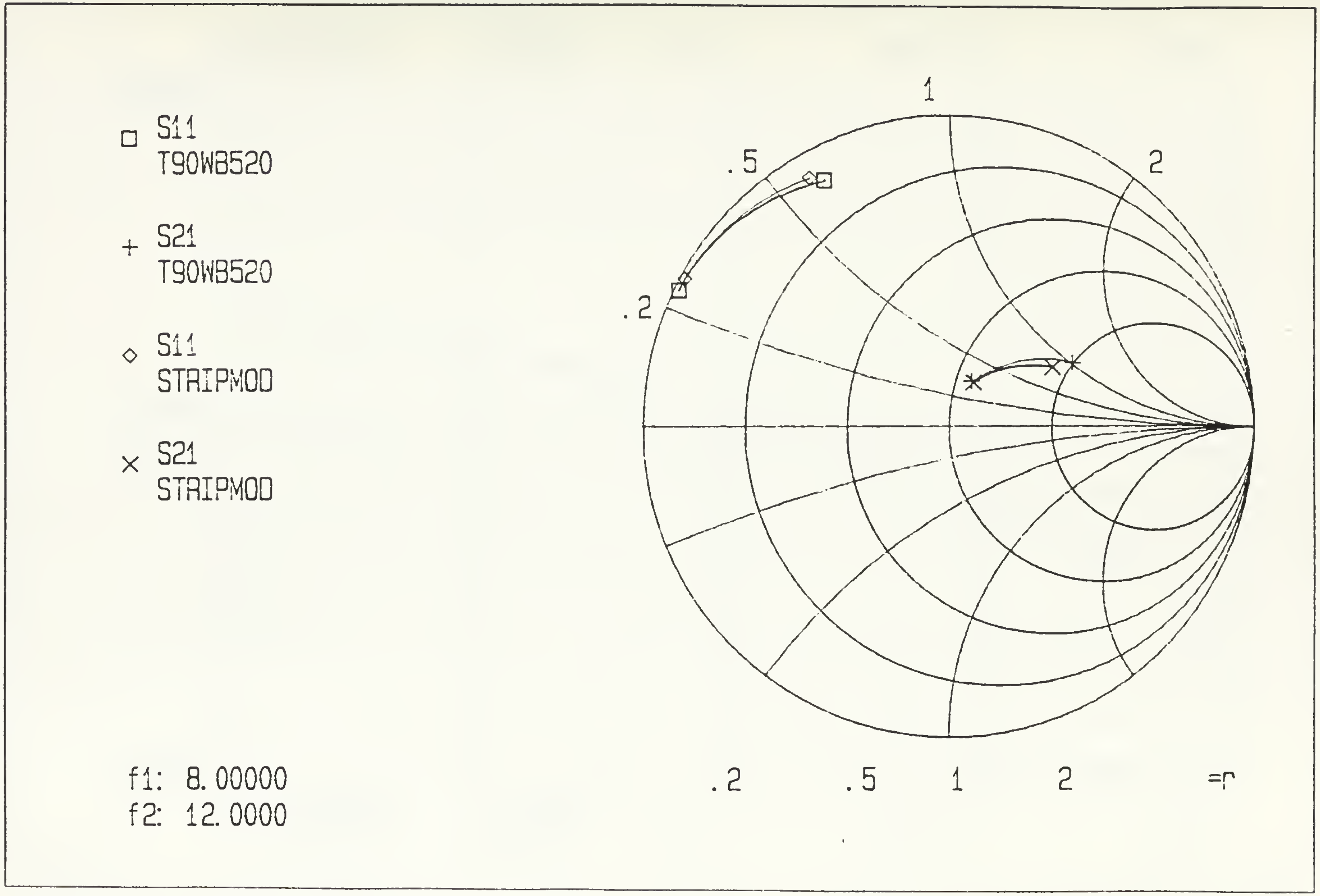


Figure 30. Smith chart plot of computed and predicted values of S_{11} and S21 for a T = 200 mils inductive strip centered in WR(90) fin-line, W/b = 0.5, E_{r2} = 1. Model inductance L = 8.20 nH.

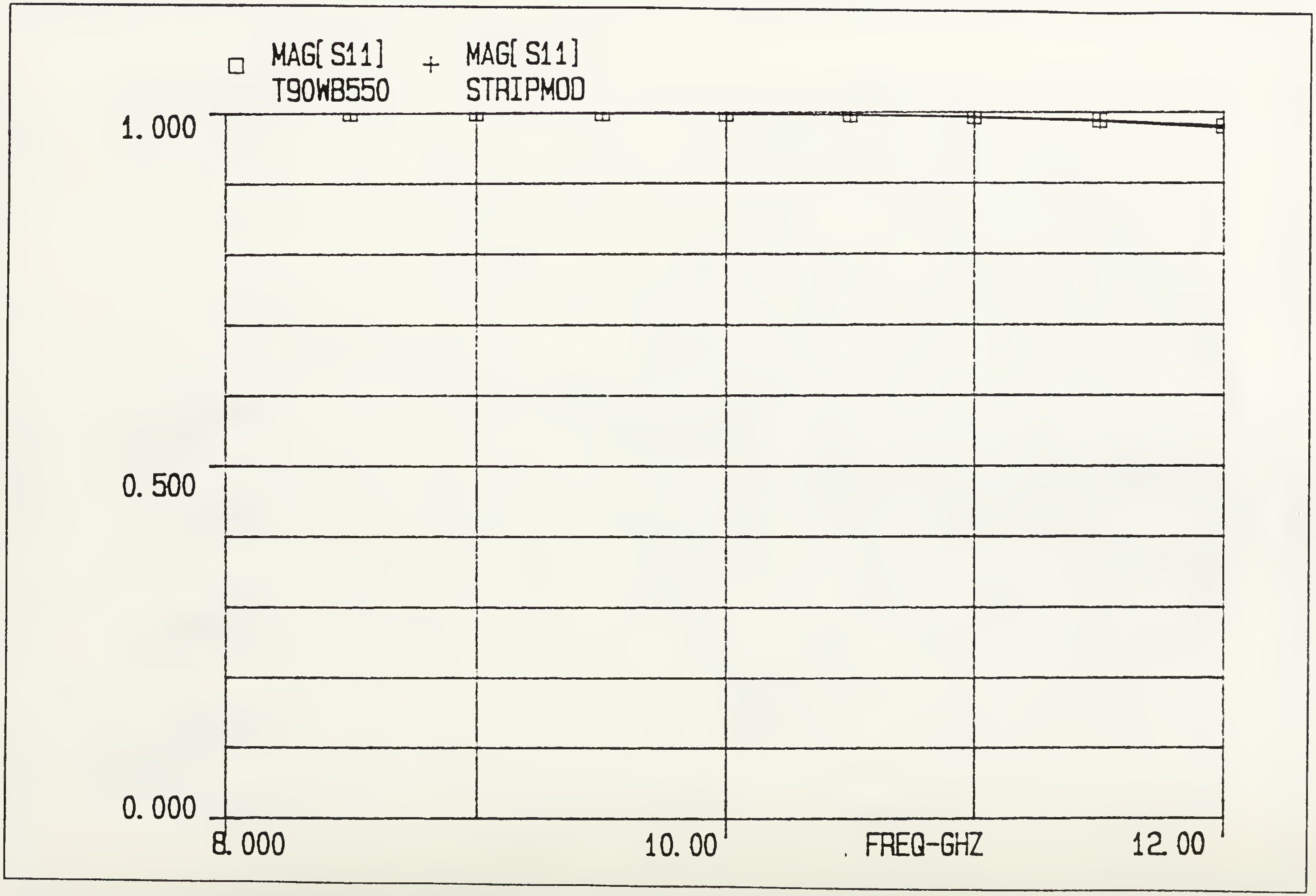


Figure 31. Computed and predicted values of $|S_{11}|$ vs. frequency for a T = 500 mils inductive strip centered in WR(90) fin-line, W/b = 0.5, E_{r2} = 1. Model inductance L = 5.90 nH.

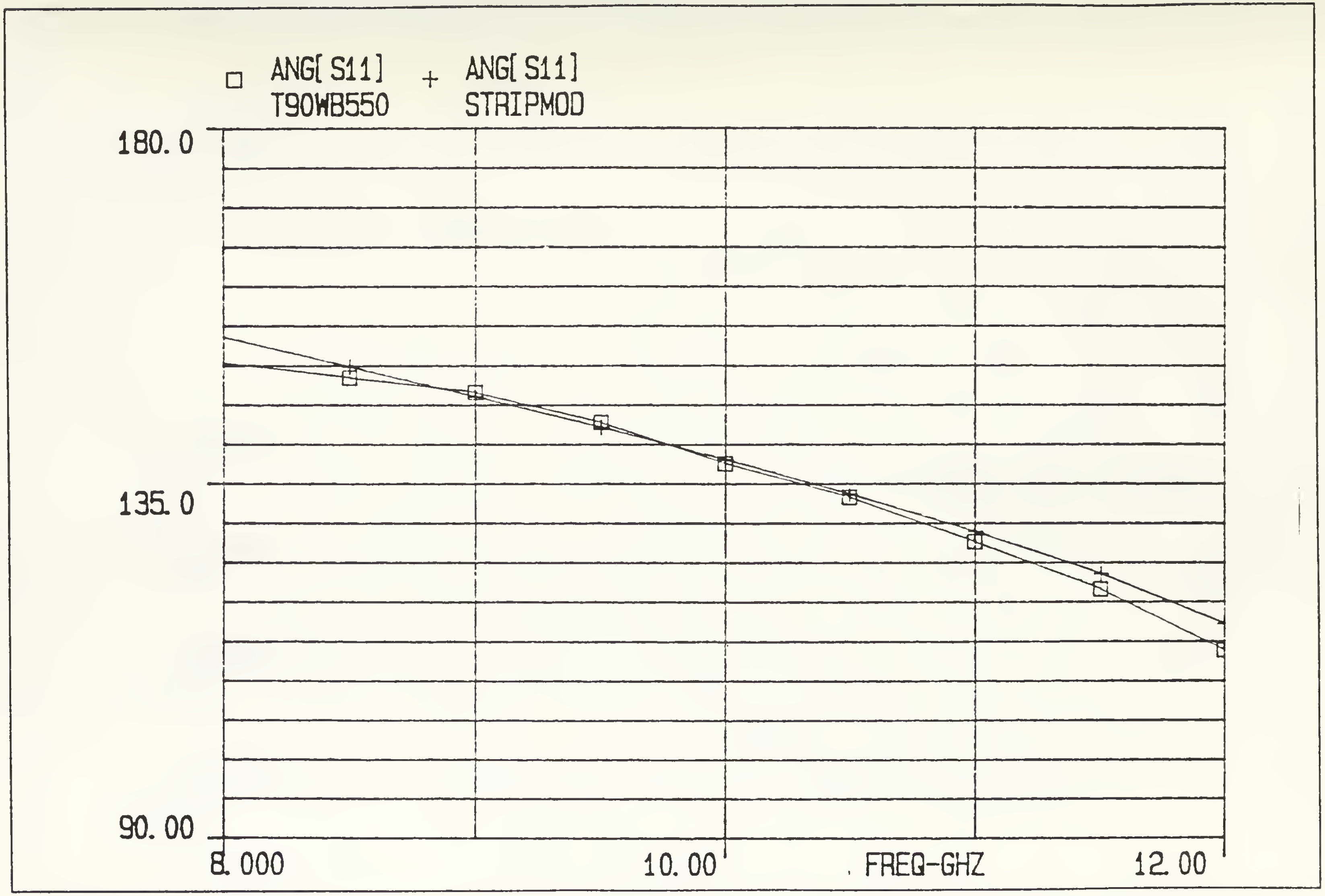


Figure 32. Computed and predicted values of $\angle S_{11}$ vs. frequency for a T = 500 mils inductive strip centered in WR(90) fin-line, W/b = 0.5, E_{r2} = 1. Model inductance L = 5.90 nH.

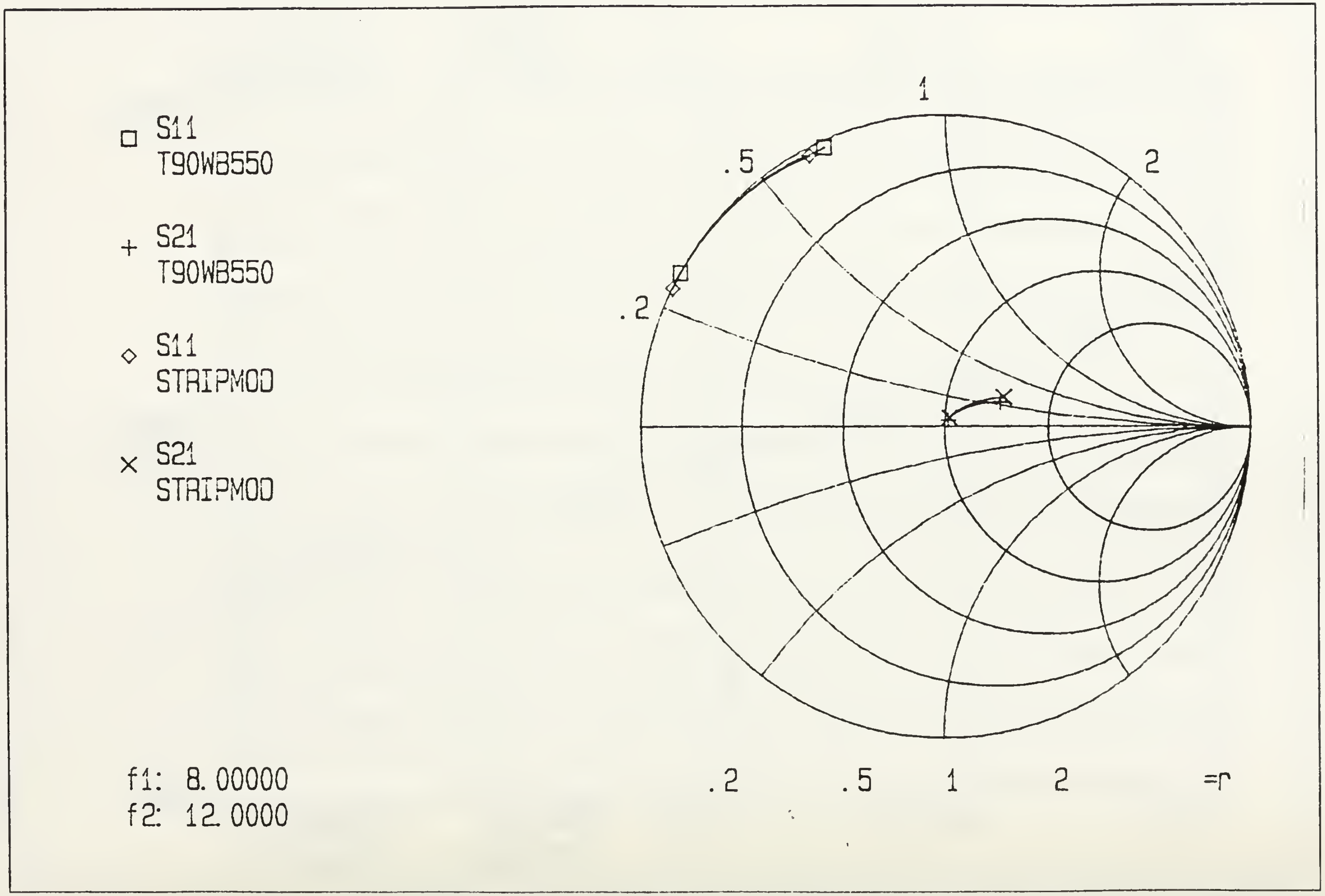


Figure 33. Smith chart plot of computed and predicted values of S_{11} and S21 for a T = 500 mils inductive strip centered in WR(90) fin-line, W/b = 0.5, E_{r2} = 1. Model inductance L = 5.90 nH.

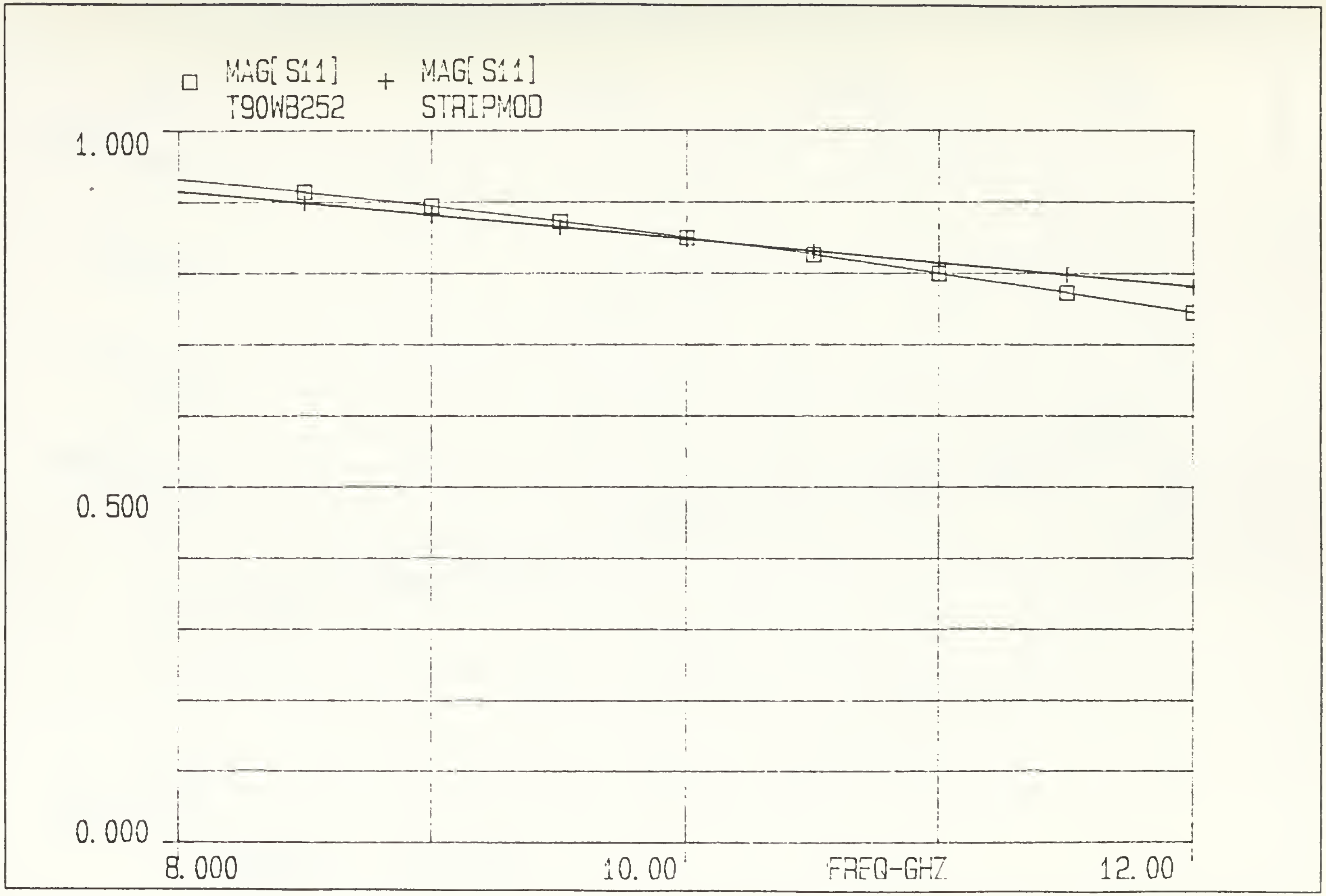


Figure 34. Computed and predicted values of $|S_{11}|$ vs. frequency for a T = 20 mils inductive strip centered in WR(90) fin-line, **W/b = 0.25, E_{r2} = 1. Model inductance L = 6.60 nH.**

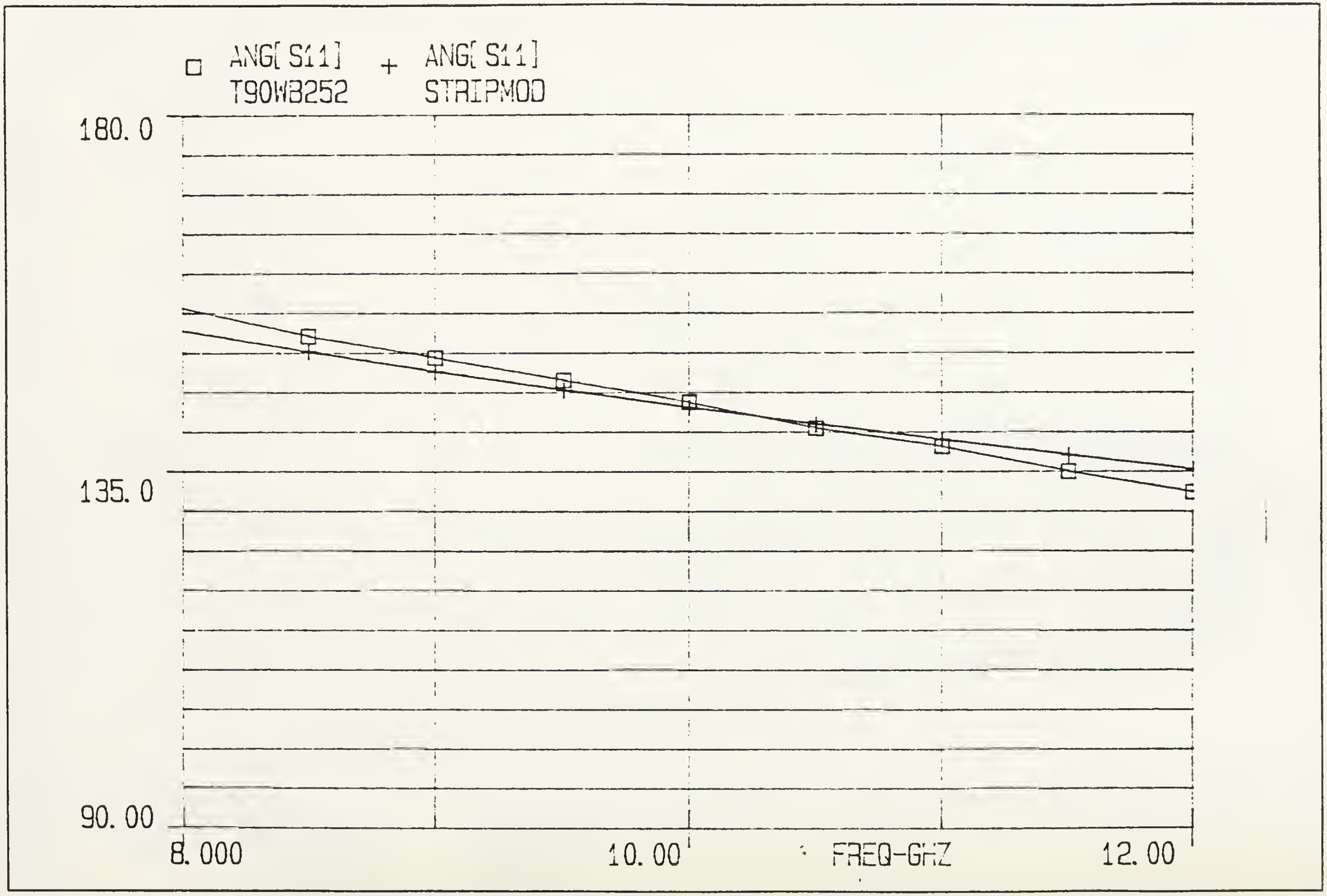


Figure 35. Computed and predicted values of θ_{11} vs. frequency for a T = 20 mils inductive strip centered in WR(90) fin-line, **W/b = 0.25, E_{r2} = 1. Model inductance L = 6.60 nH.**

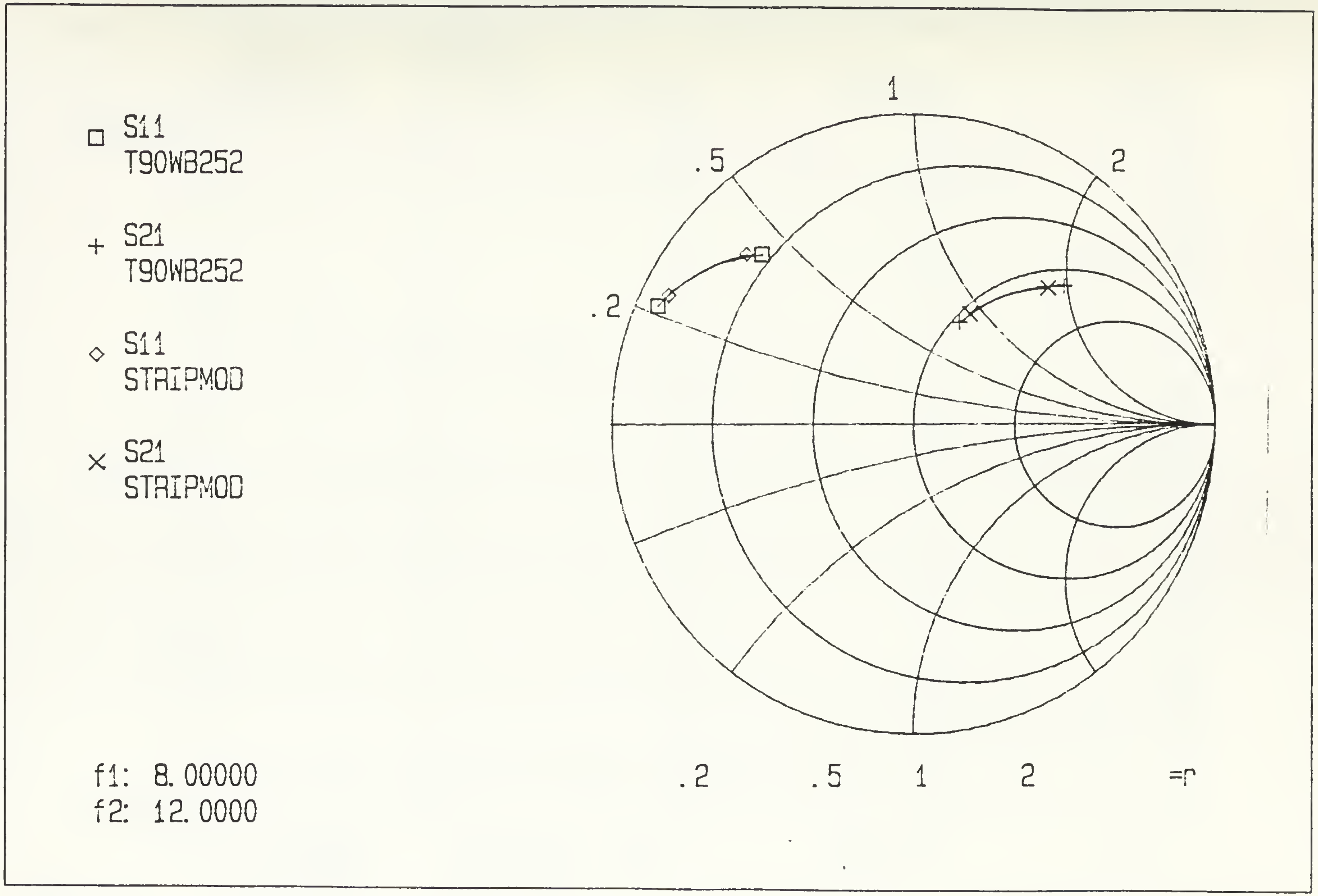


Figure 36. Smith chart plot of computed and predicted values of S_{11} and S21 for a T = 20 mils inductive strip centered in **WR(90) fin-line, W/b = 0.25, E_{r2} = 1. Model inductance L = 6.60 nH.**

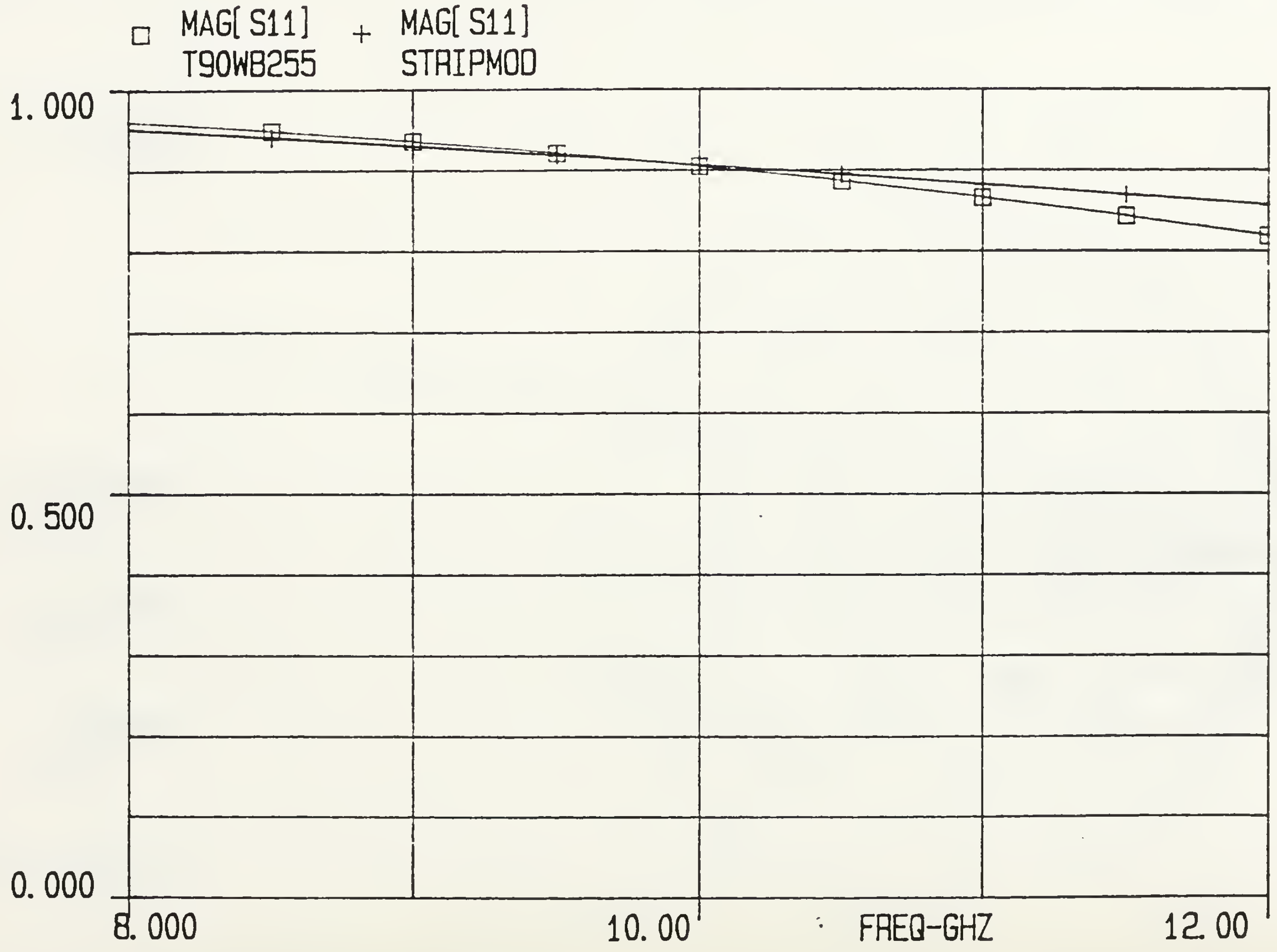


Figure 37. Computed and predicted values of $|S_{11}|$ vs. frequency for a T = 50 mils inductive strip centered in WR(90) finline, W/b = 0.25, $E_{r2} = 1$. Model inductance L = 5.65 nH.

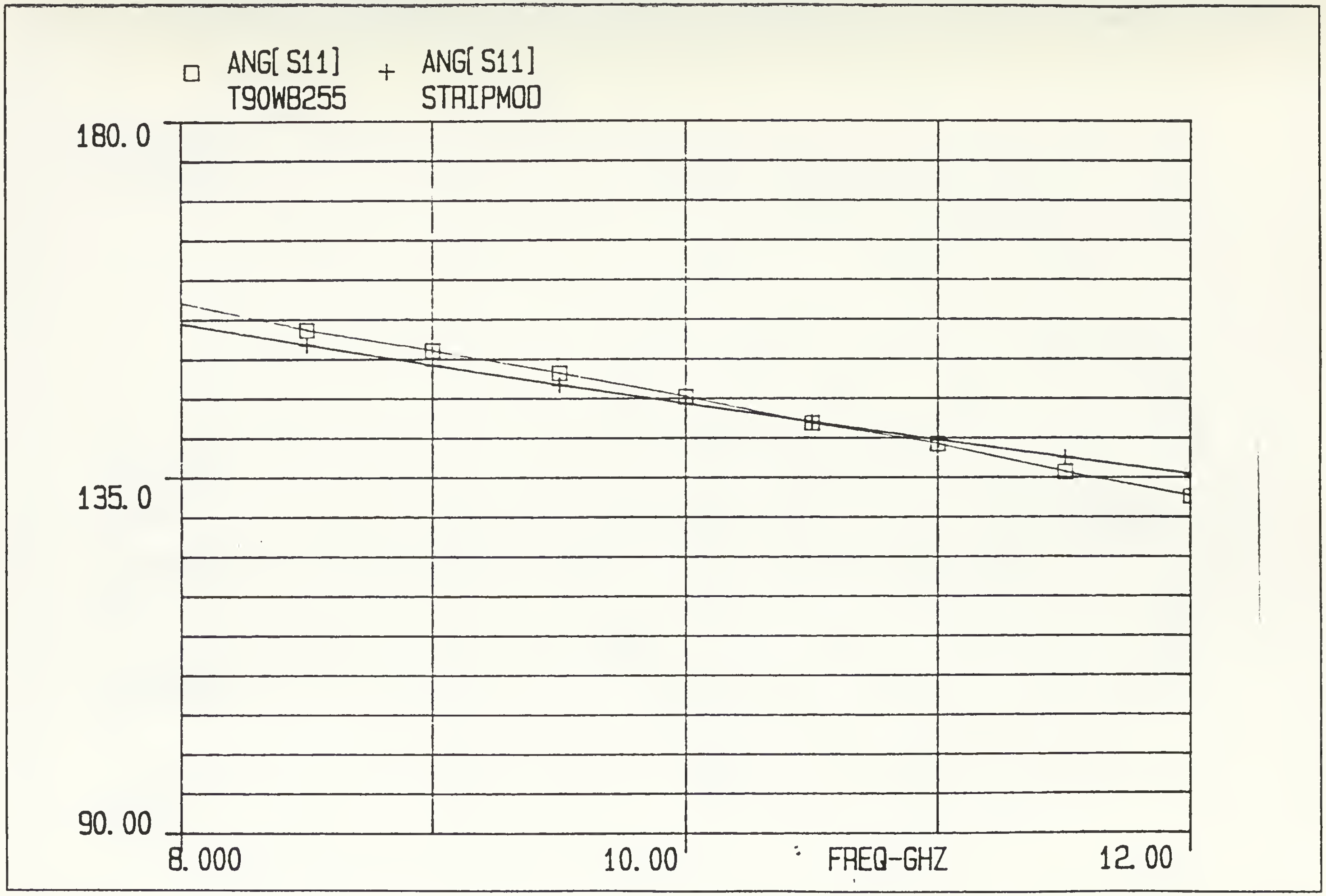


Figure 38. Computed and predicted values of θ_{11} vs. frequency for a T = 50 mils inductive strip centered in WR(90) fin-line, W/b = 0.25, $E_{r2} = 1$. Model inductance L = 5.65 nH.

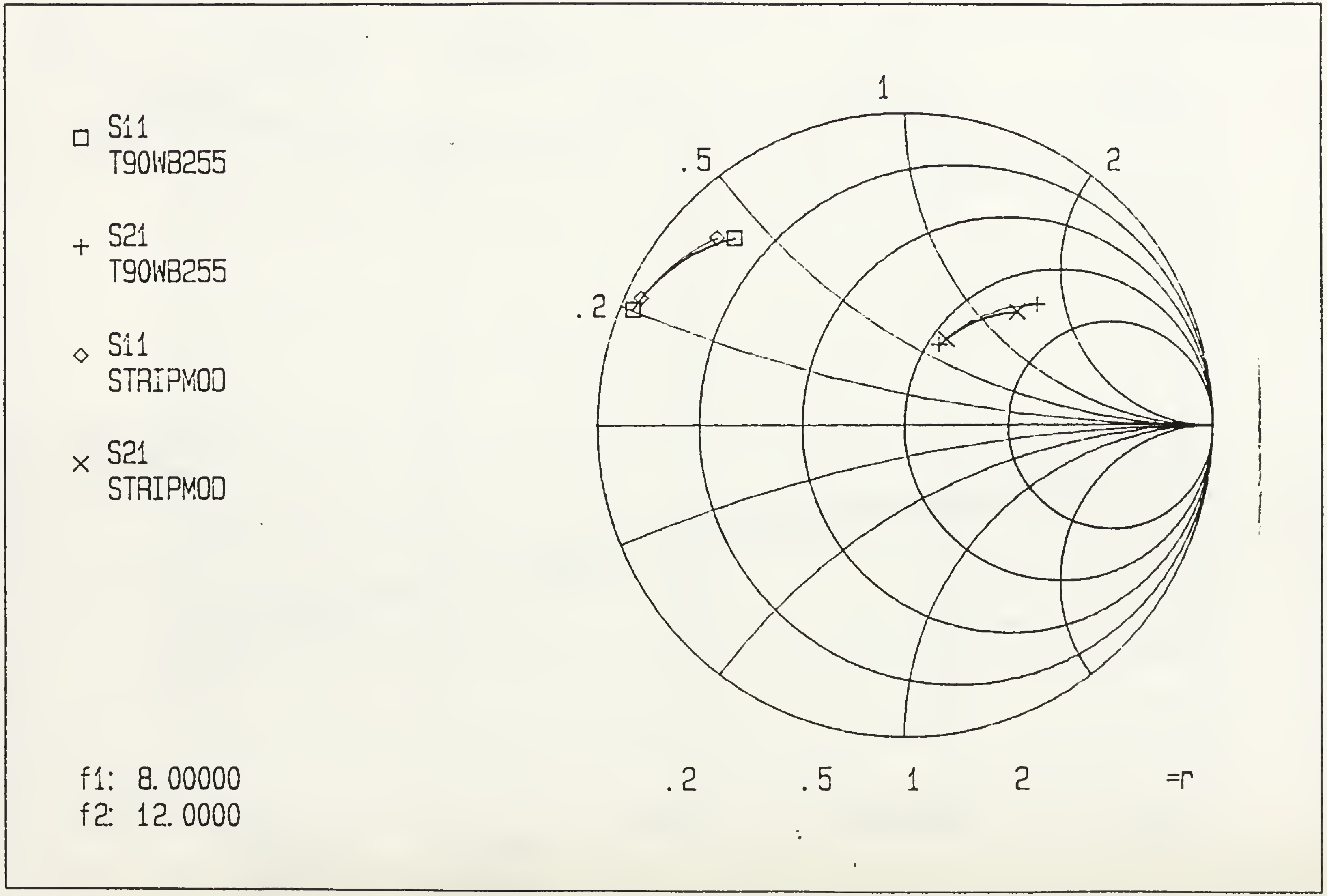


Figure 39. Smith chart plot of computed and predicted values of S_{11} and S21 for a T = 50 mils inductive strip centered in WR(90) fin-line, W/b = 0.25, E_{r2} = 1. Model inductance L = 5.65 nH.

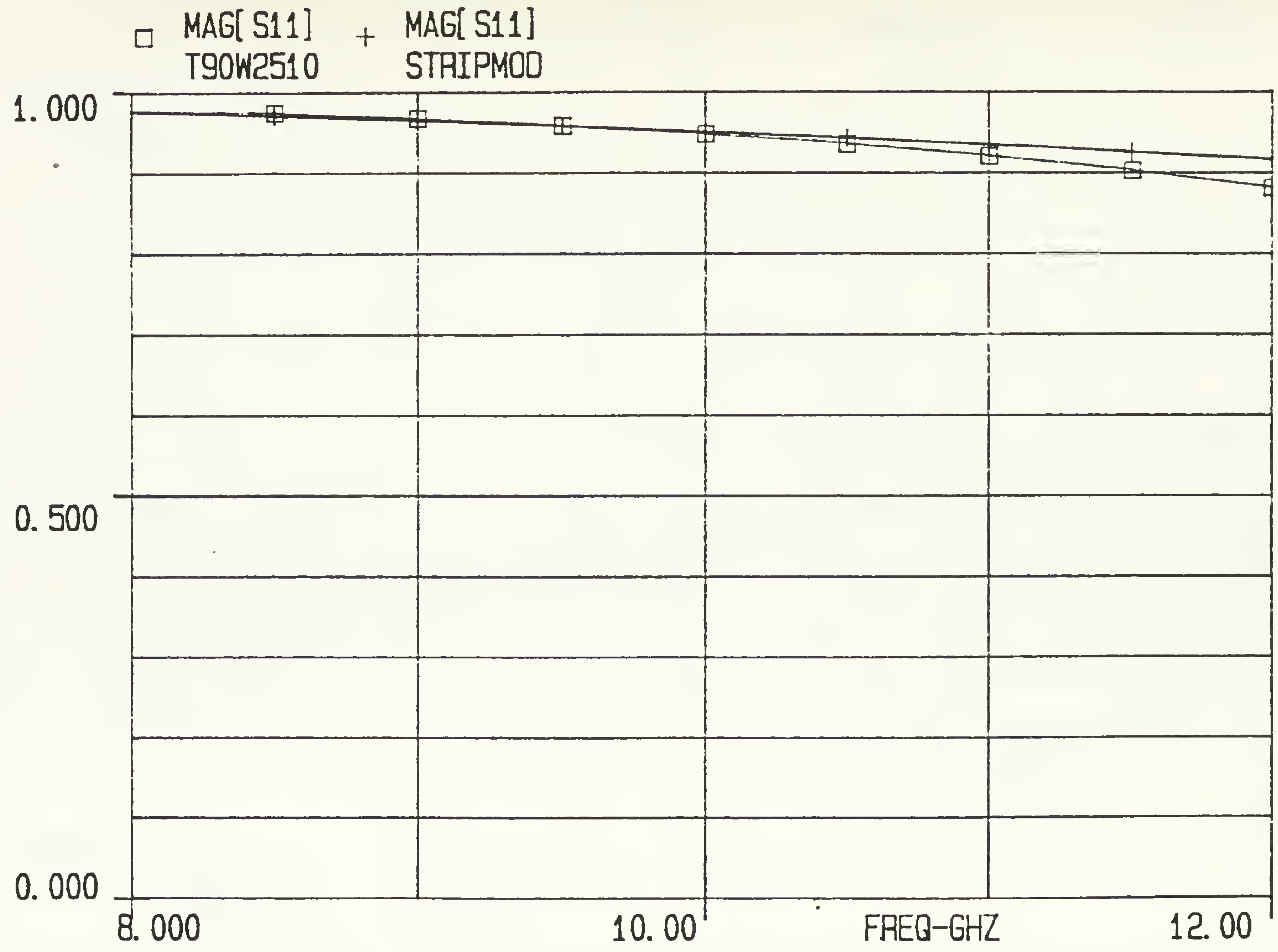


Figure 40. Computed and predicted values of $|S_{11}|$ vs. frequency for a T = 100 mils inductive strip centered in WR(90) fin-line, W/b = 0.25, E_{r2} = 1. Model inductance L = 5.005 nH.

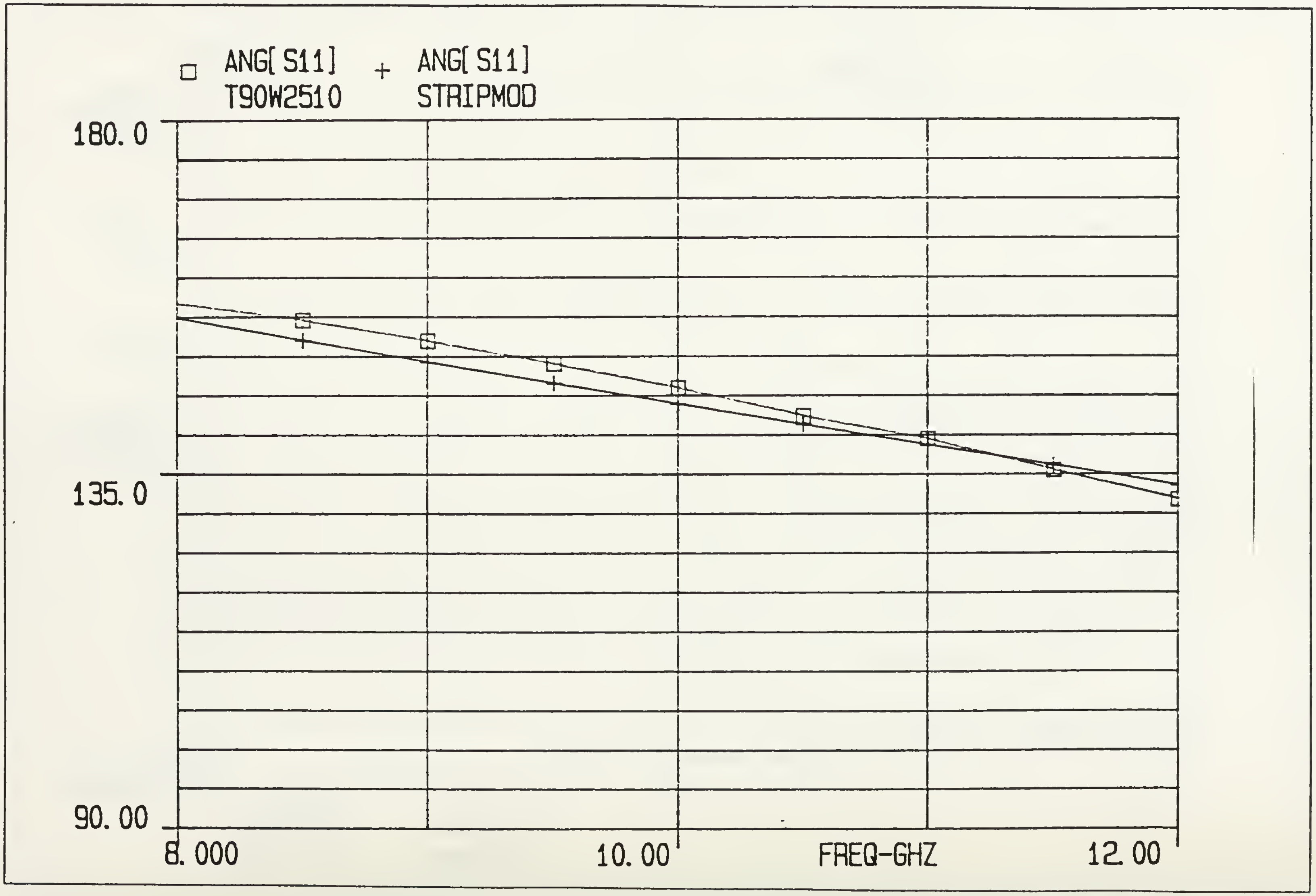


Figure 41. Computed and predicted values of θ_{11} vs. frequency for a T = 100 mils inductive strip centered in WR(90) finline, W/b = 0.25, E_{r2} = 1. Model inductance L = 5.005 nH.

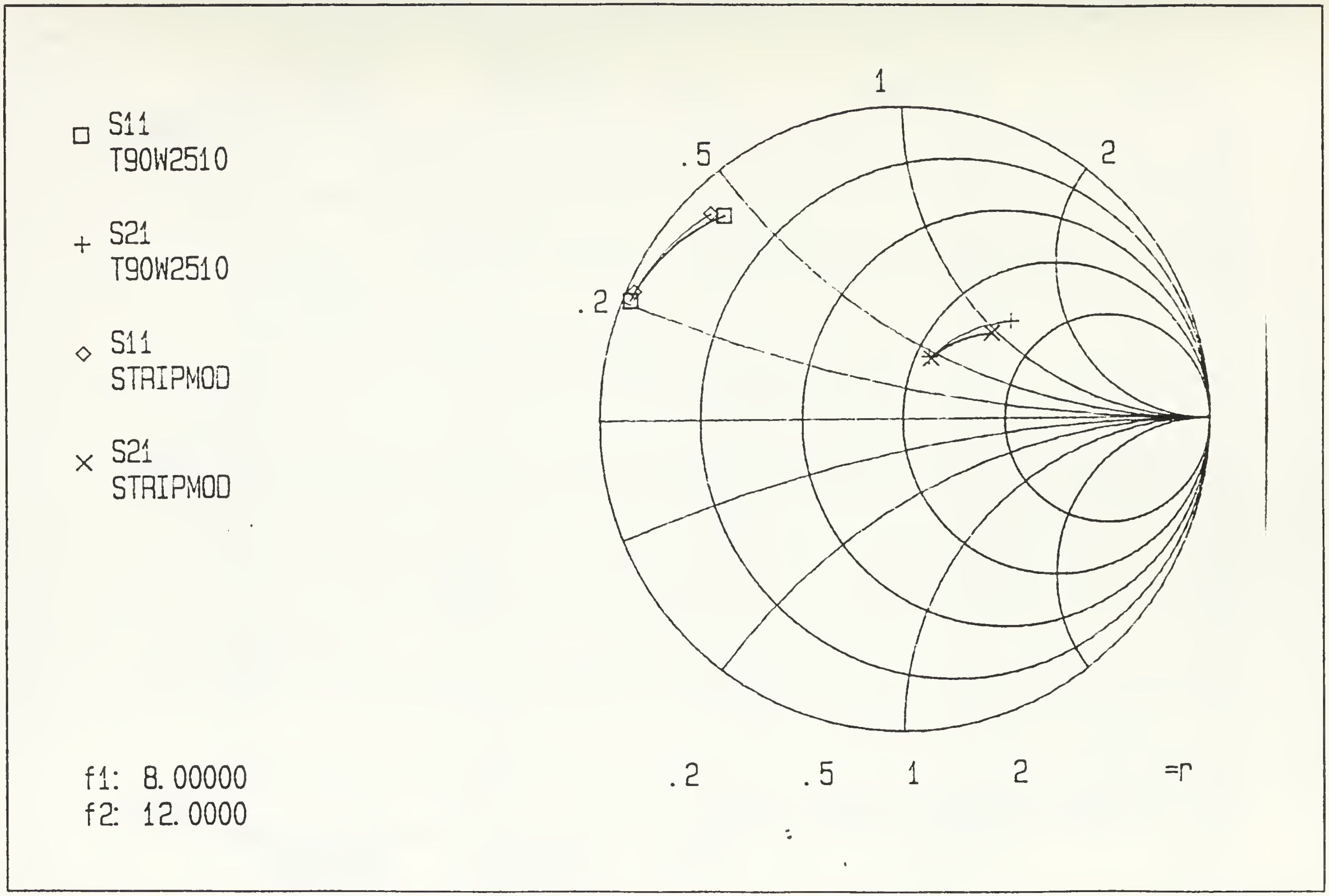


Figure 42. Smith chart plot of computed and predicted values of S_{11} and S21 for a T = 100 mils inductive strip centered in WR(90) fin-line, W/b = 0.25, E_{r2} = 1. Model inductance L = 5.005 nH.

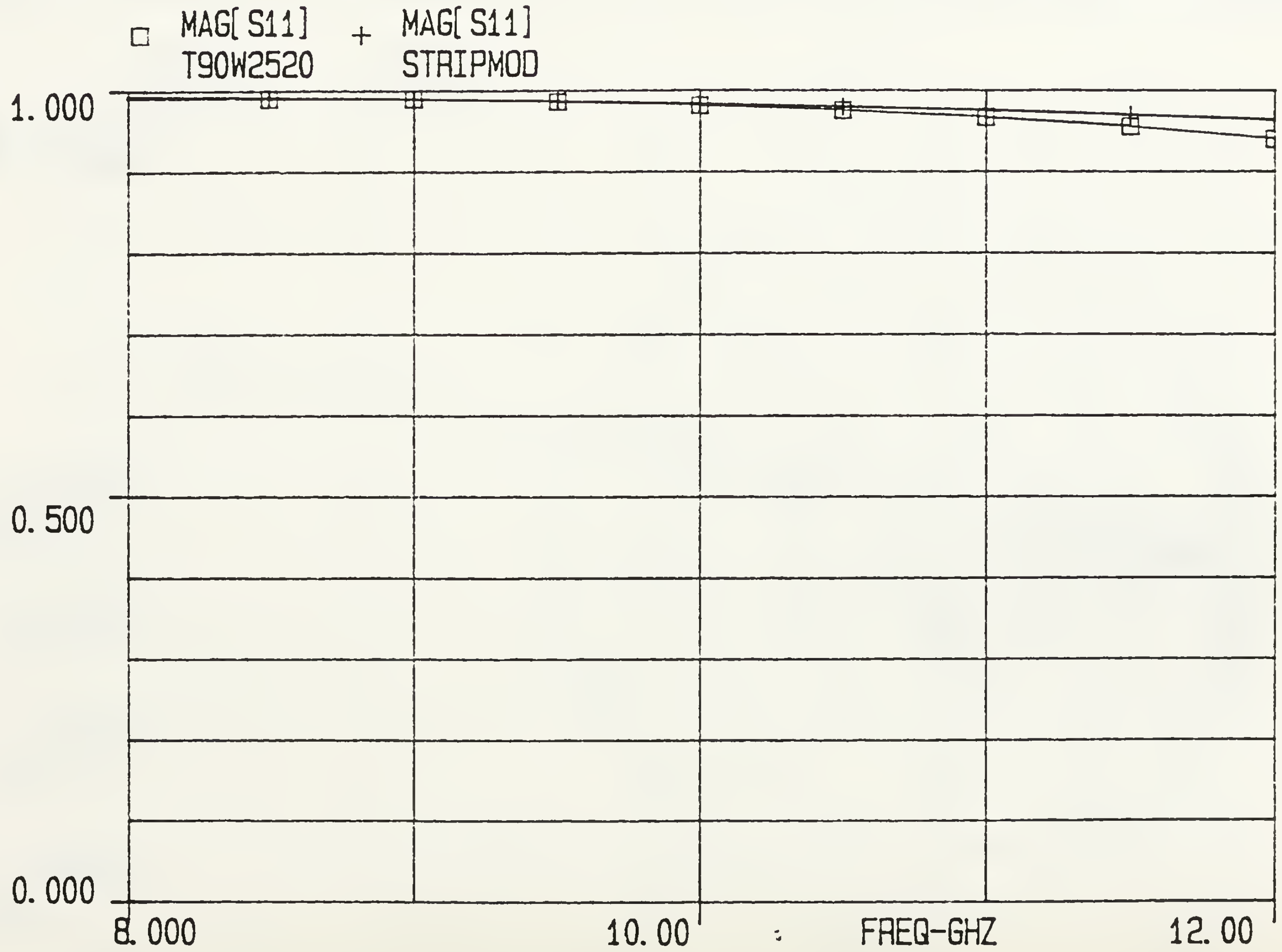


Figure 43. Computed and predicted values of $|S_{11}|$ vs. frequency for a T = 200 mils inductive strip centered in WR(90) fin-line, W/b = 0.25, $E_{r2} = 1$. Model inductance L = 4.20 nH.

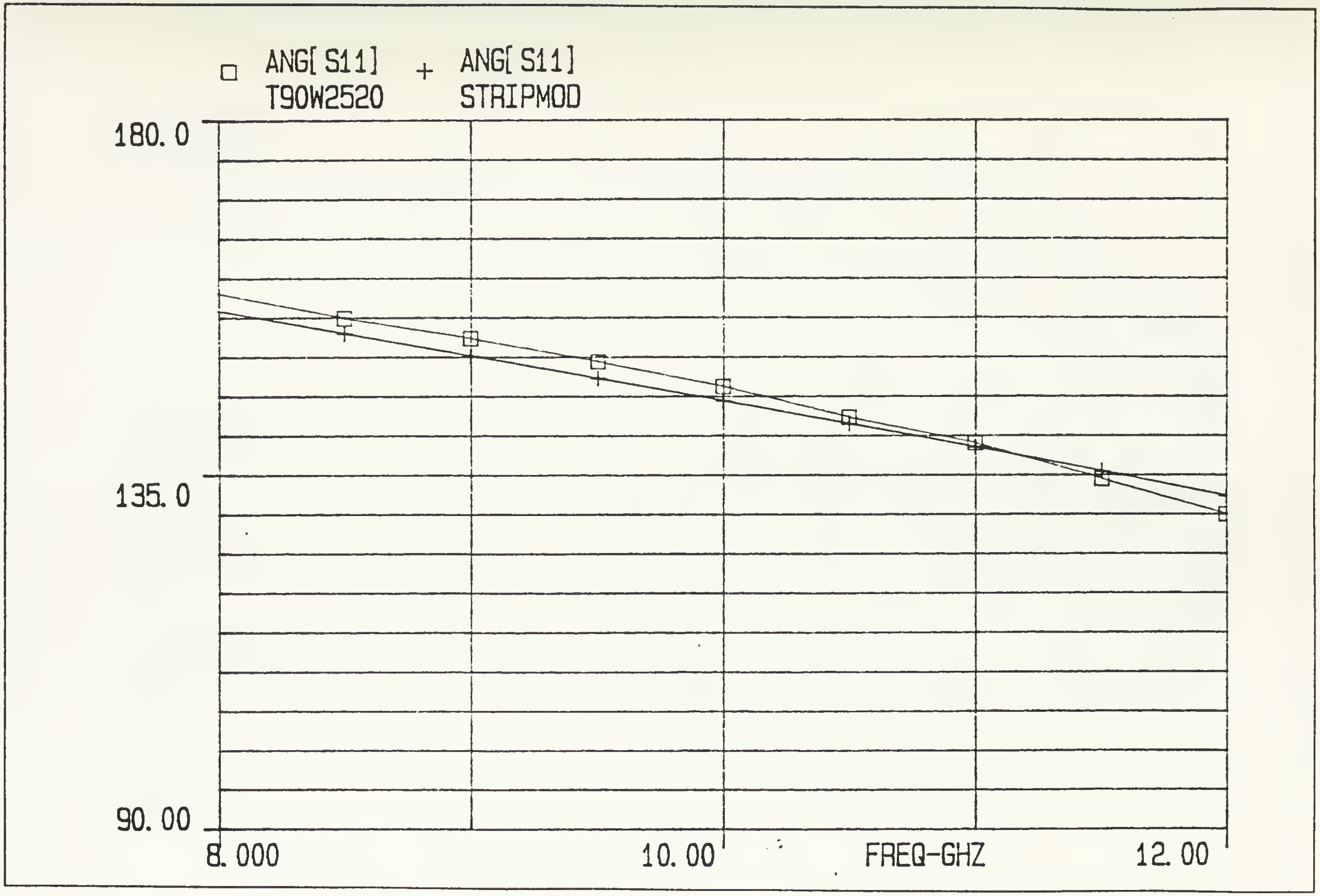


Figure 44. Computed and predicted values of θ_{11} vs. frequency for a T = 200 mils inductive strip centered in WR(90) finline, **W/b = 0.25, E_{r2} = 1. Model inductance L = 4.20 nH.**

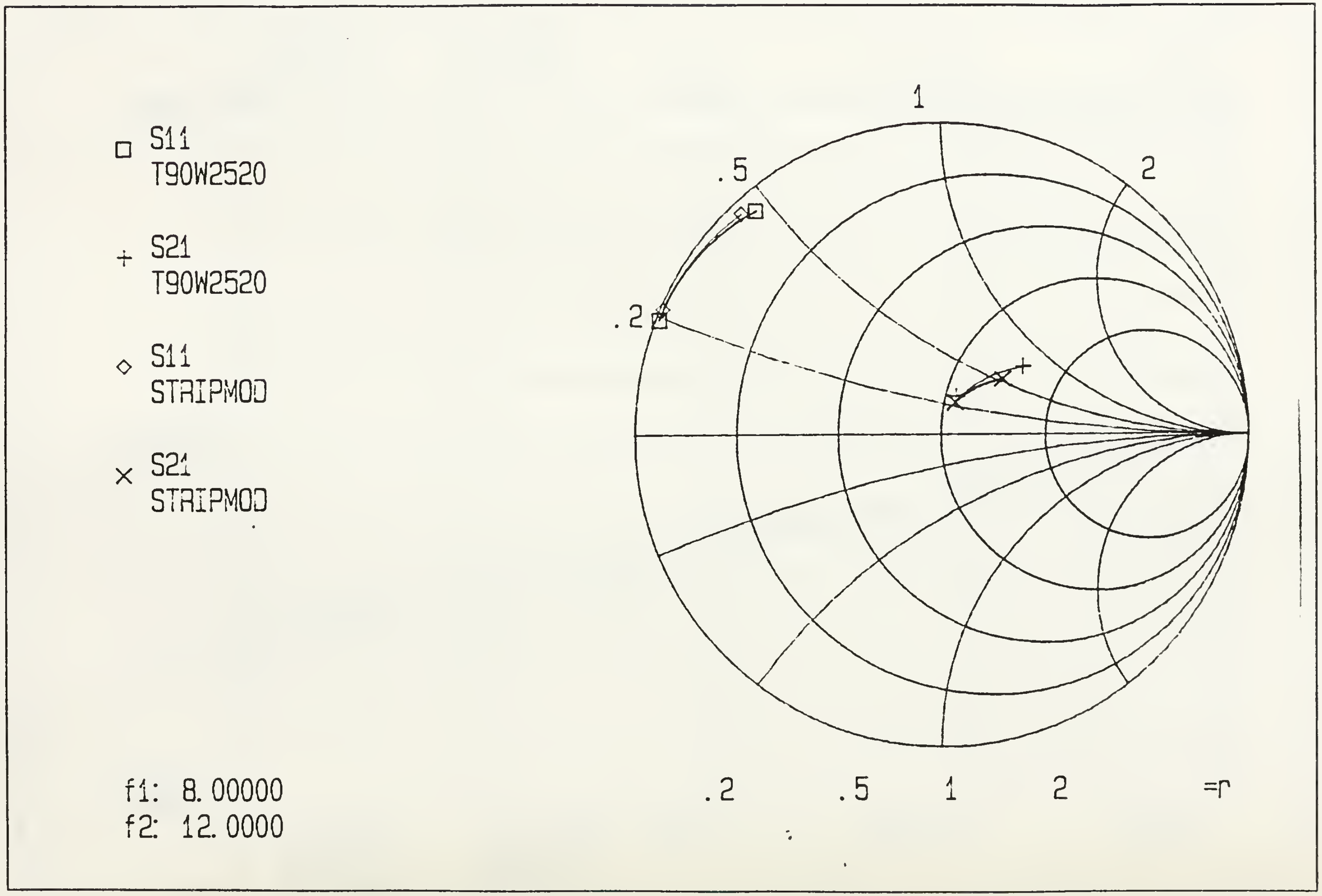


Figure 45. Smith chart plot of computed and predicted values of S_{11} and S21 for a T = 200 mils inductive strip centered in WR(90) fin-line, W/b = 0.25, $E_{r2} = 1$. Model inductance L = 4.20 nH.

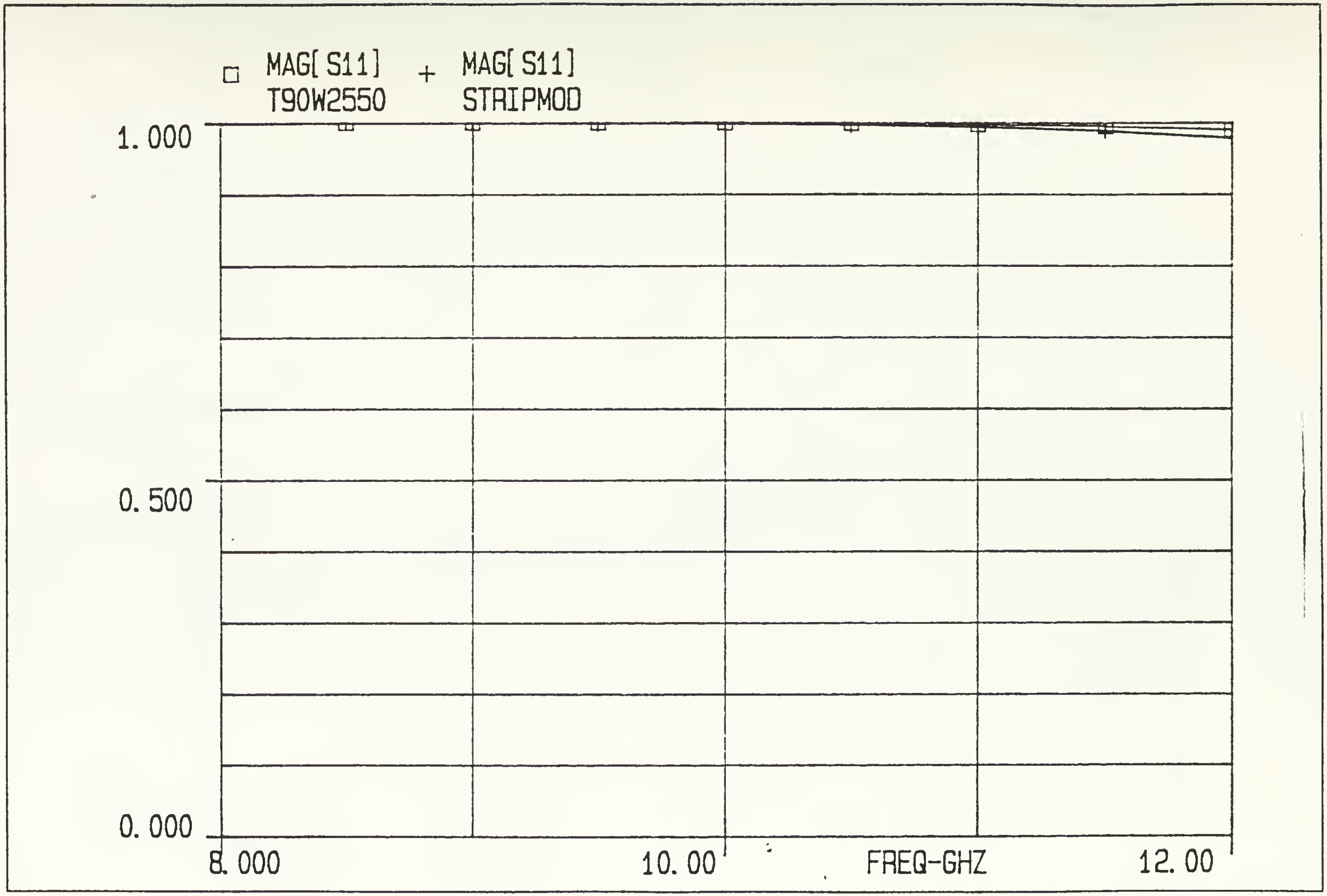


Figure 46. Computed and predicted values of $|S_{11}|$ vs. frequency for a T = 500 mils inductive strip centered in WR(90) fin-line, W/b = 0.25, E_{r2} = 1. Model inductance L = 3.82 nH.

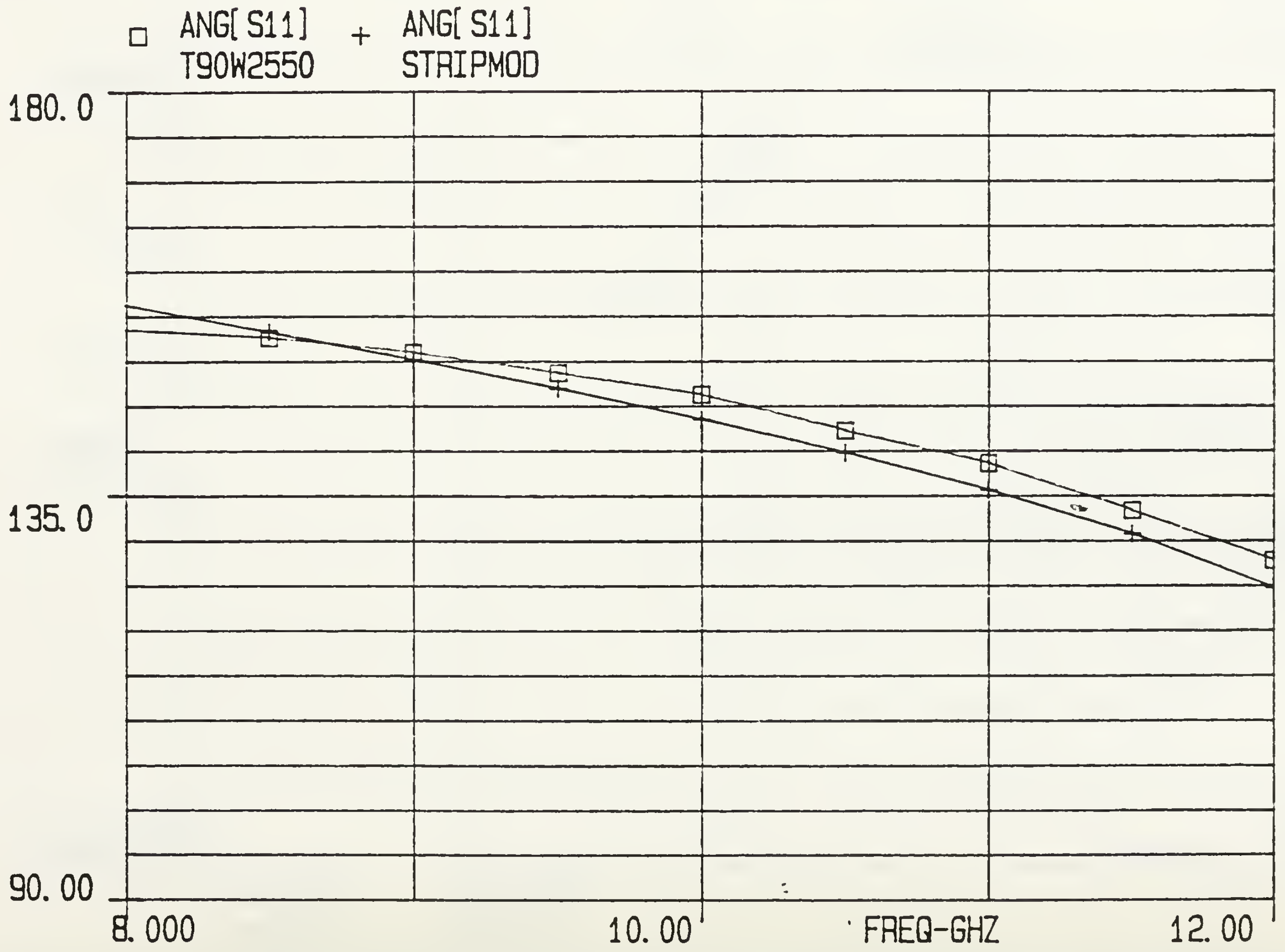


Figure 47. Computed and predicted values of θ_{11} vs. frequency for a T = 500 mils inductive strip centered in WR(90) fin-line, W/b = 0.25, E_{r2} = 1 Model inductance L = 3.82 nH.

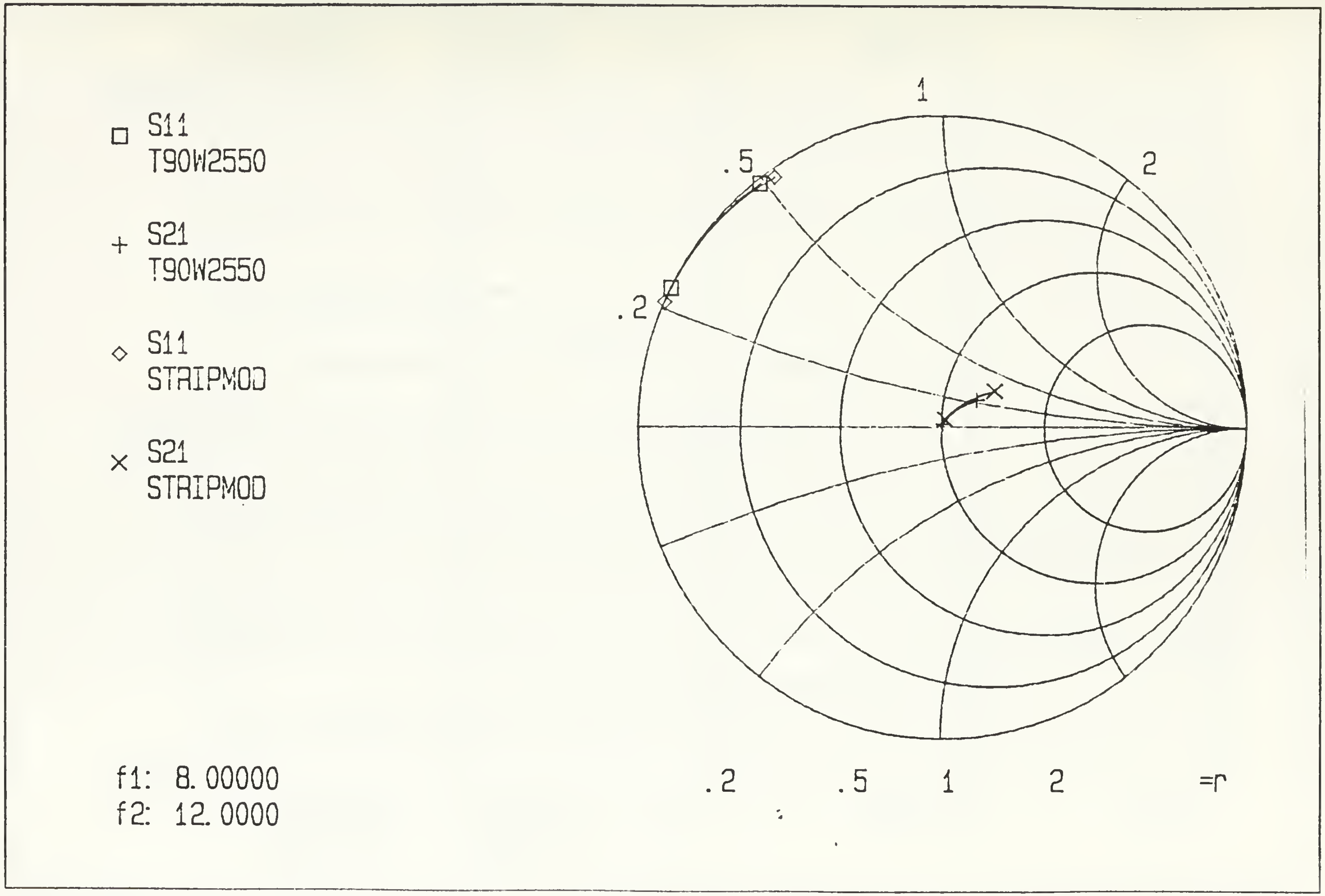


Figure 48. Smith chart plot of computed and predicted values of S_{11} and S21 for a T = 500 mils inductive strip centered in WR(90) fin-line, W/b = 0.25, E_{r2} = 1 Model inductance L = 3.82 nH.

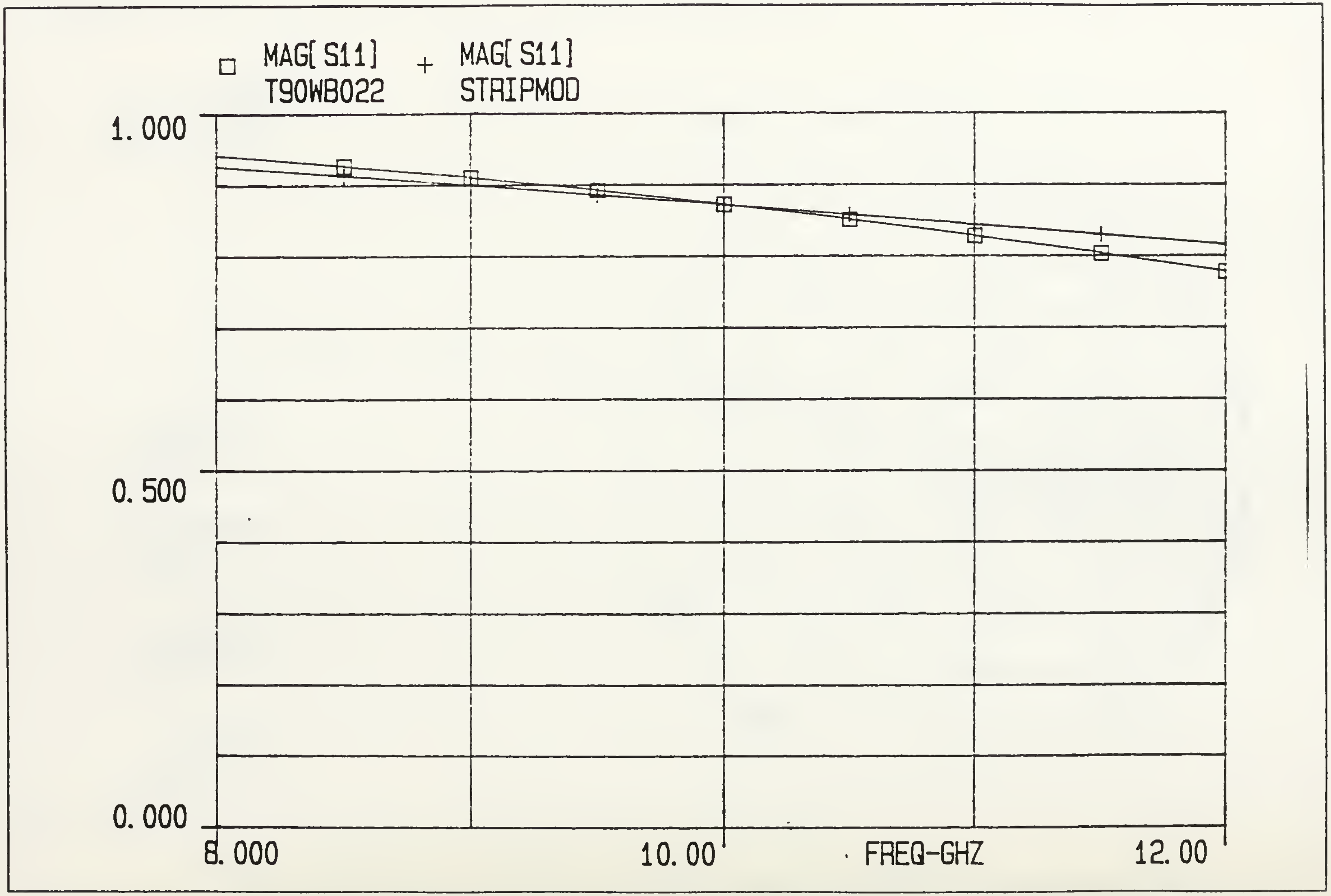


Figure 49. Computed and predicted values of $|S_{11}|$ vs. frequency for a T = 20 mils inductive strip centered in WR(90) finline, W/b = 0.2, E_{r2} = 1. Model inductance L = 4.89 nH.

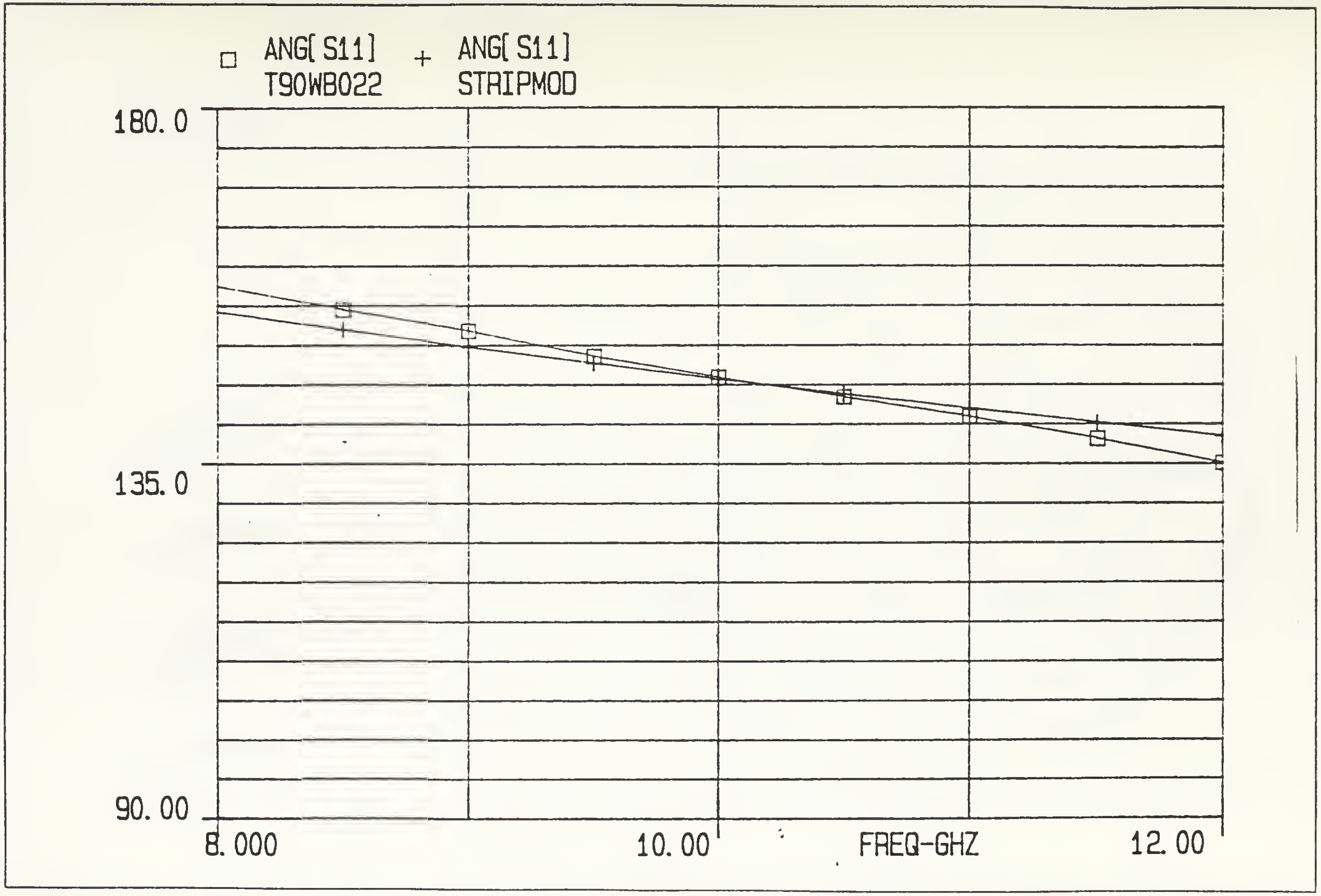


Figure 50. Computed and predicted values of θ_{11} vs. frequency for a T = 20 mils inductive strip centered in WR(90) fin-line, W/b = 0.2, E_{r2} = 1. Model inductance L = 4.89 nH.

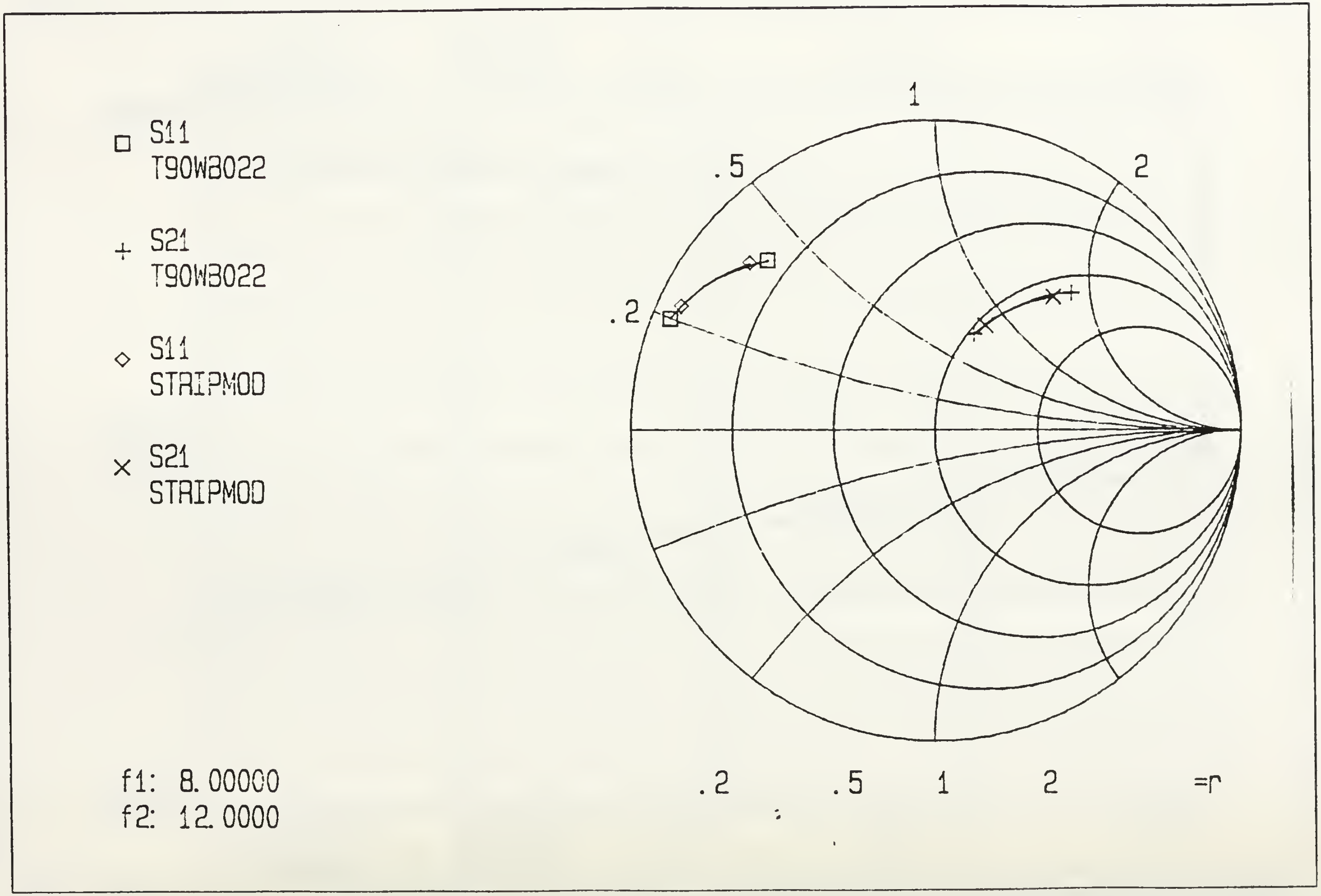


Figure 51. Smith chart plot of computed and predicted values of S_{11} and S21 for a T = 20 mils inductive strip centered in WR(90) fin-line, W/b = 0.2, E_{r2} = 1. Model inductance L = 4.89 nH.

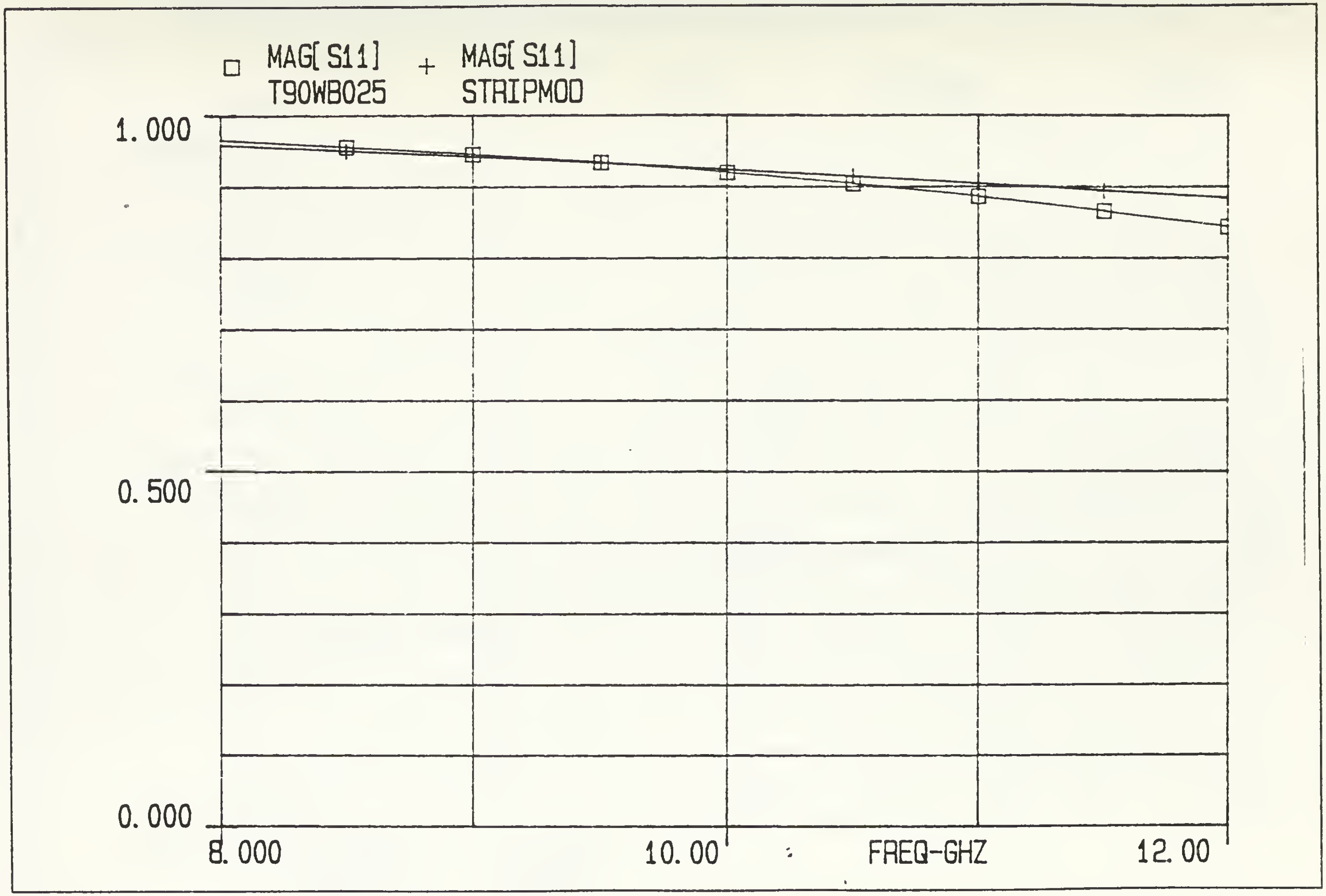


Figure 52. Computed and predicted values of $|S_{11}|$ vs. frequency for a T = 50 mils inductive strip centered in WR(90) fin-line, **W/b = 0.2, E_{r2} = 1. Model inductance L = 4.18 nH.**

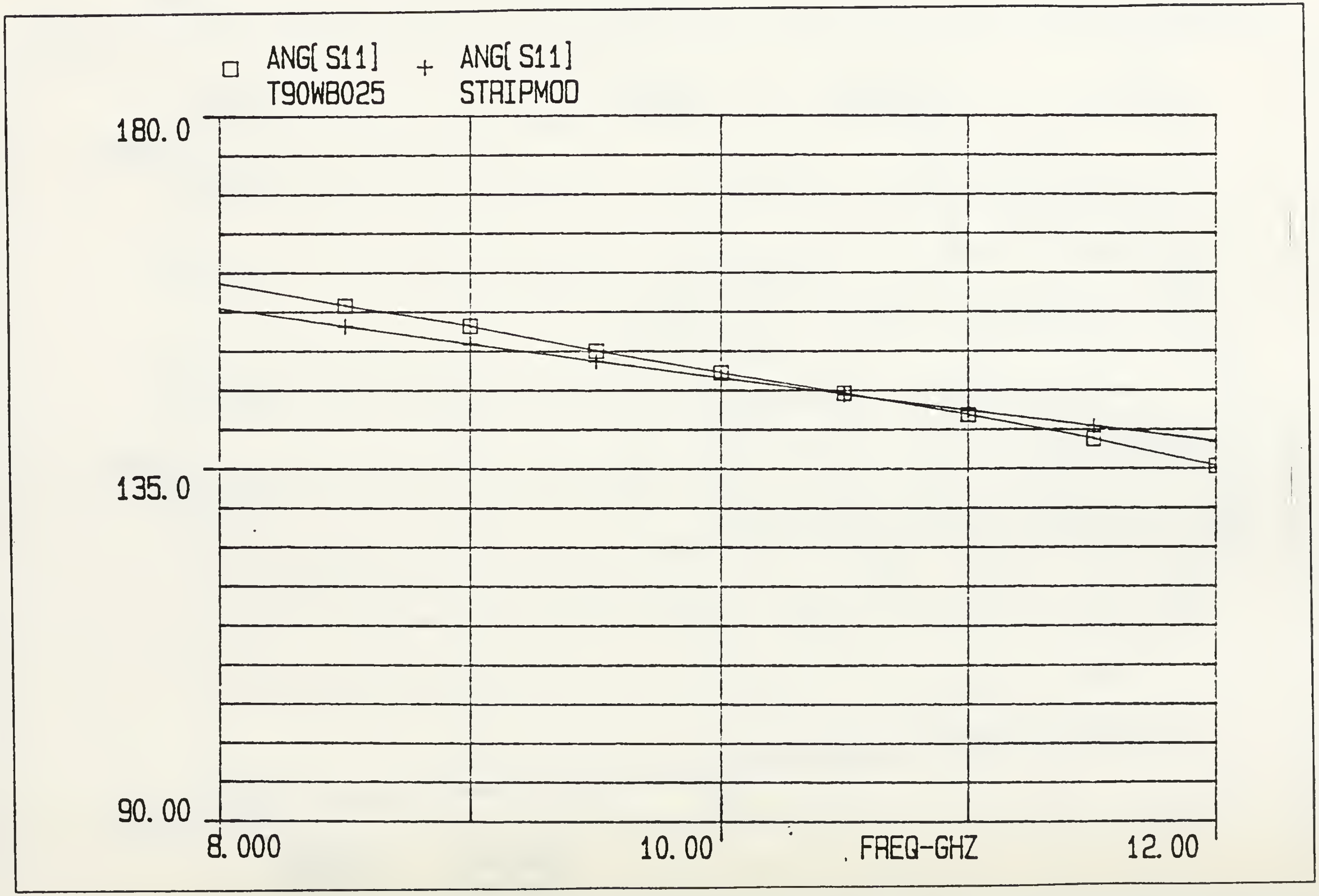


Figure 53. Computed and predicted values of θ_{11} vs. frequency for a T = 50 mils inductive strip centered in WR(90) fin-line, W/b = 0.2, $E_{r2} = 1$. Model inductance L = 4.18 nH.

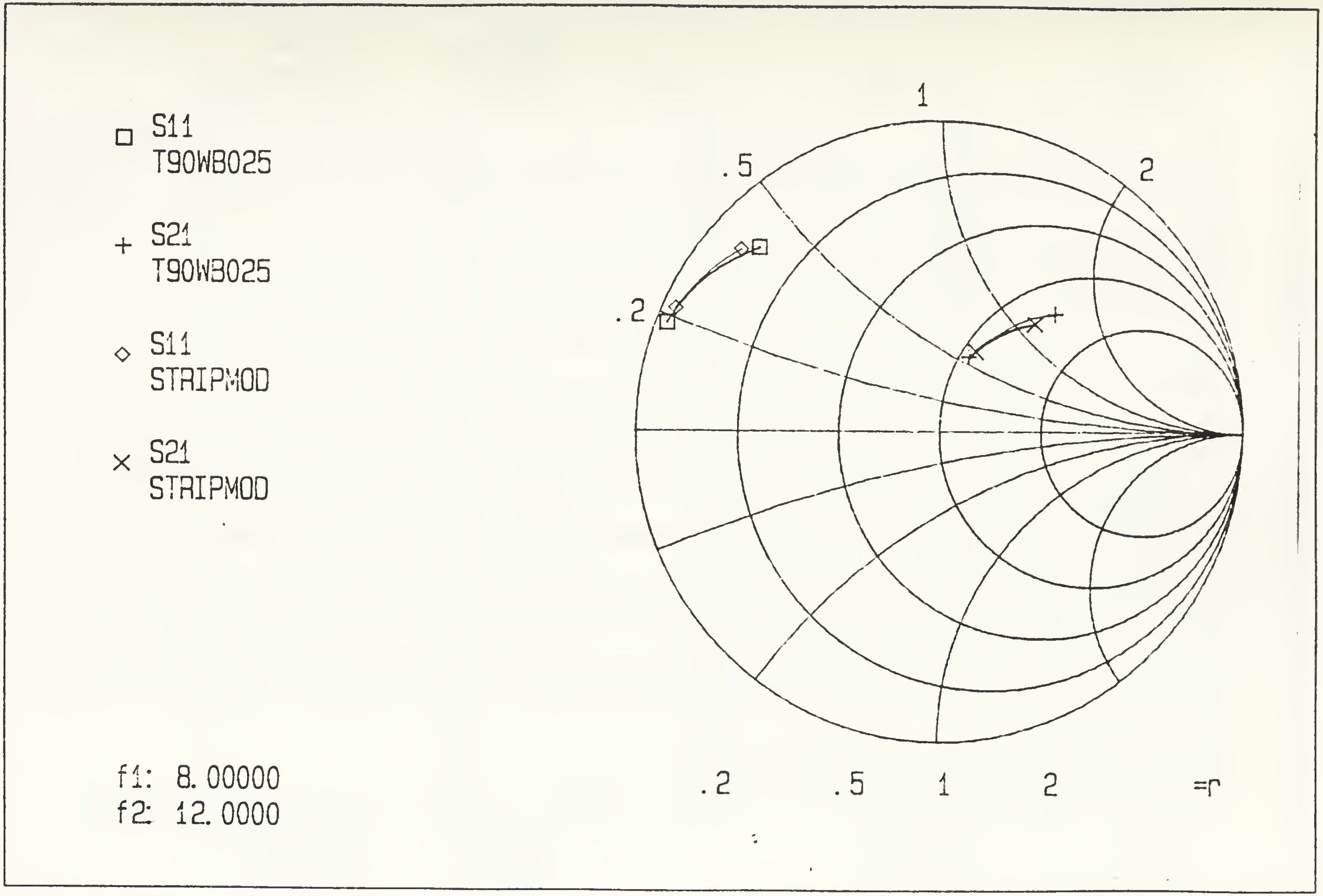


Figure 54. Smith chart plot of computed and predicted values of S_{11} and S21 for a T = 50 mils inductive strip centered in WR(90) fin-line, W/b = 0.2, E_{r2} = 1. Model inductance L = 4.18 nH.

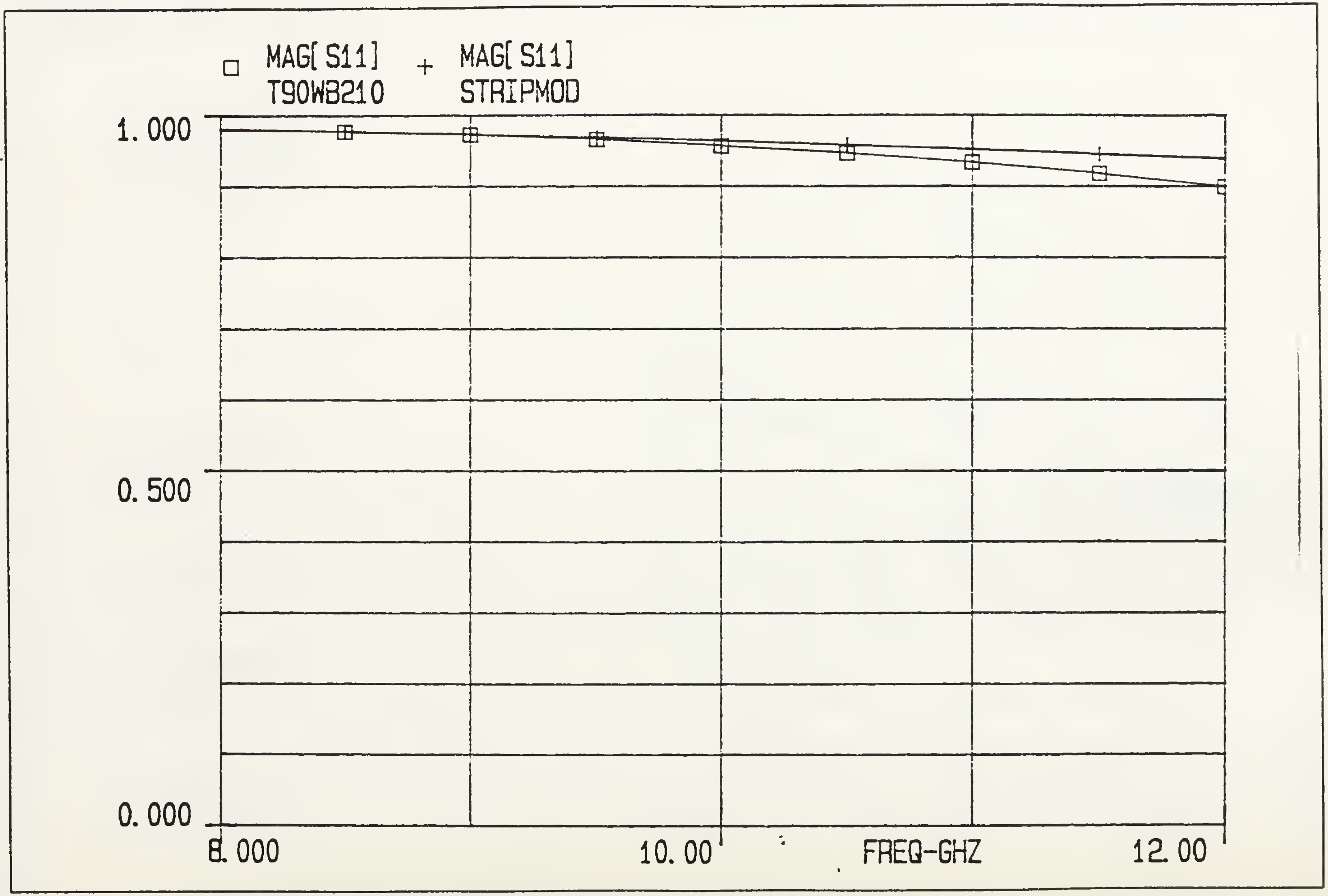


Figure 55. Computed and predicted values of $|S_{11}|$ vs. frequency for a T = 100 mils inductive strip centered in WR(90) fin-line, W/b = 0.2, E_{r2} = 1. Model inductance L = 3.55 nH.

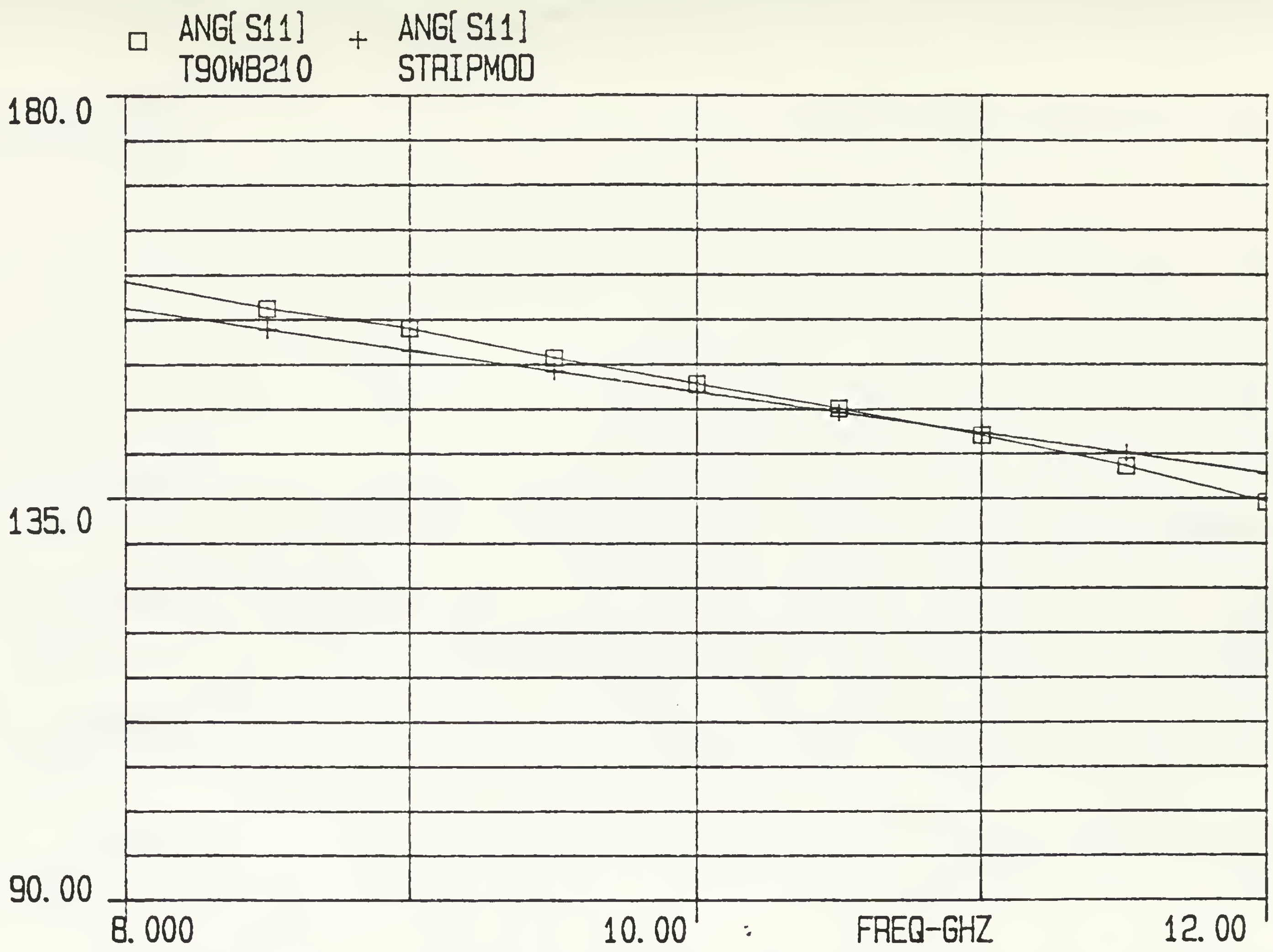


Figure 56. Computed and predicted values of θ_{11} vs. frequency for a T = 100 mils inductive strip centered in WR(90) finline, W/b = 0.2, E_{r2} = 1. Model inductance L = 3.55 nH.

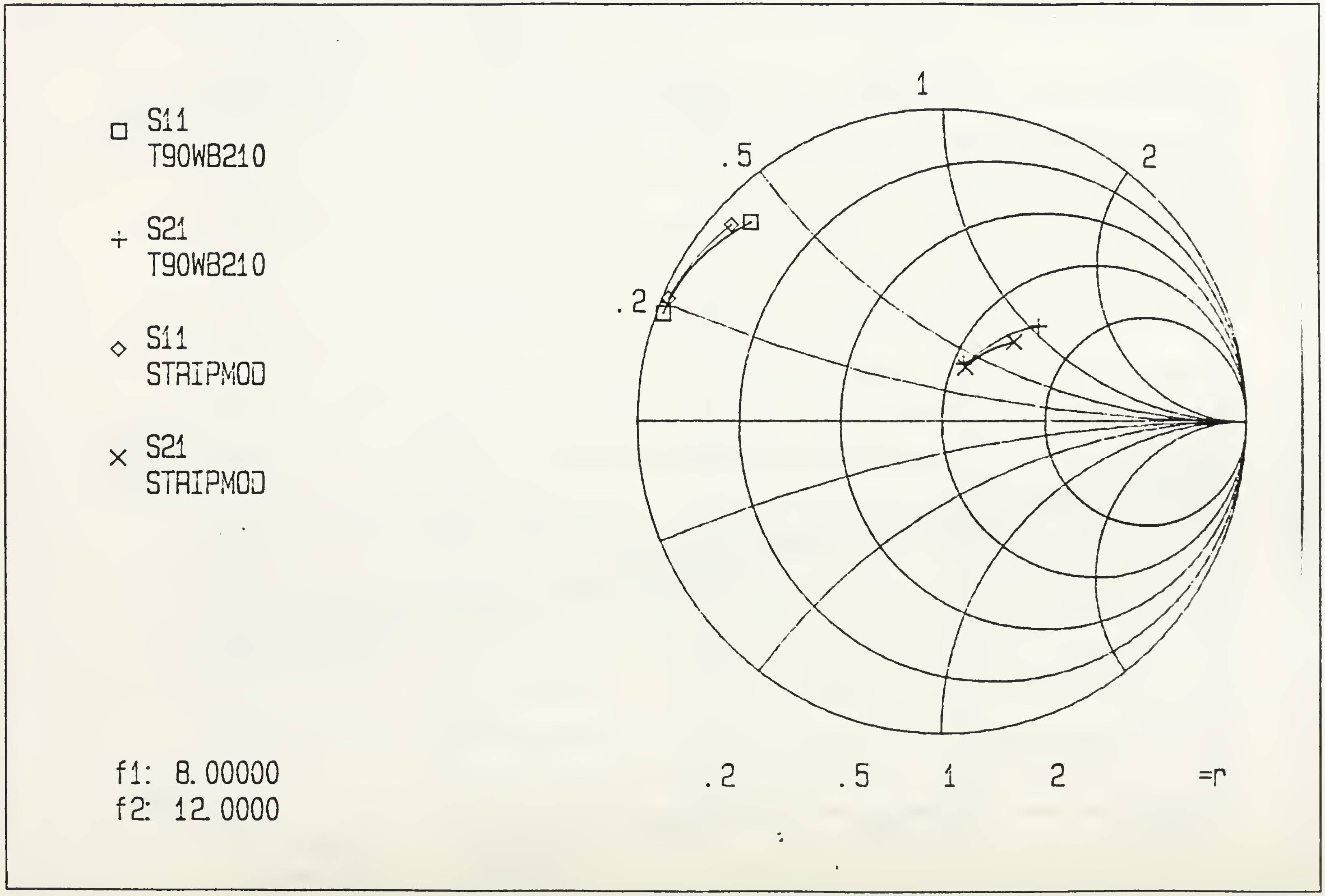


Figure 57. Smith chart plot of computed and predicted values of S_{11} and S21 for a T = 100 mils inductive strip centered in WR(90) fin-line, W/b = 0.2, $E_{r_2} = 1$. Model inductance L = 3.55 nH.

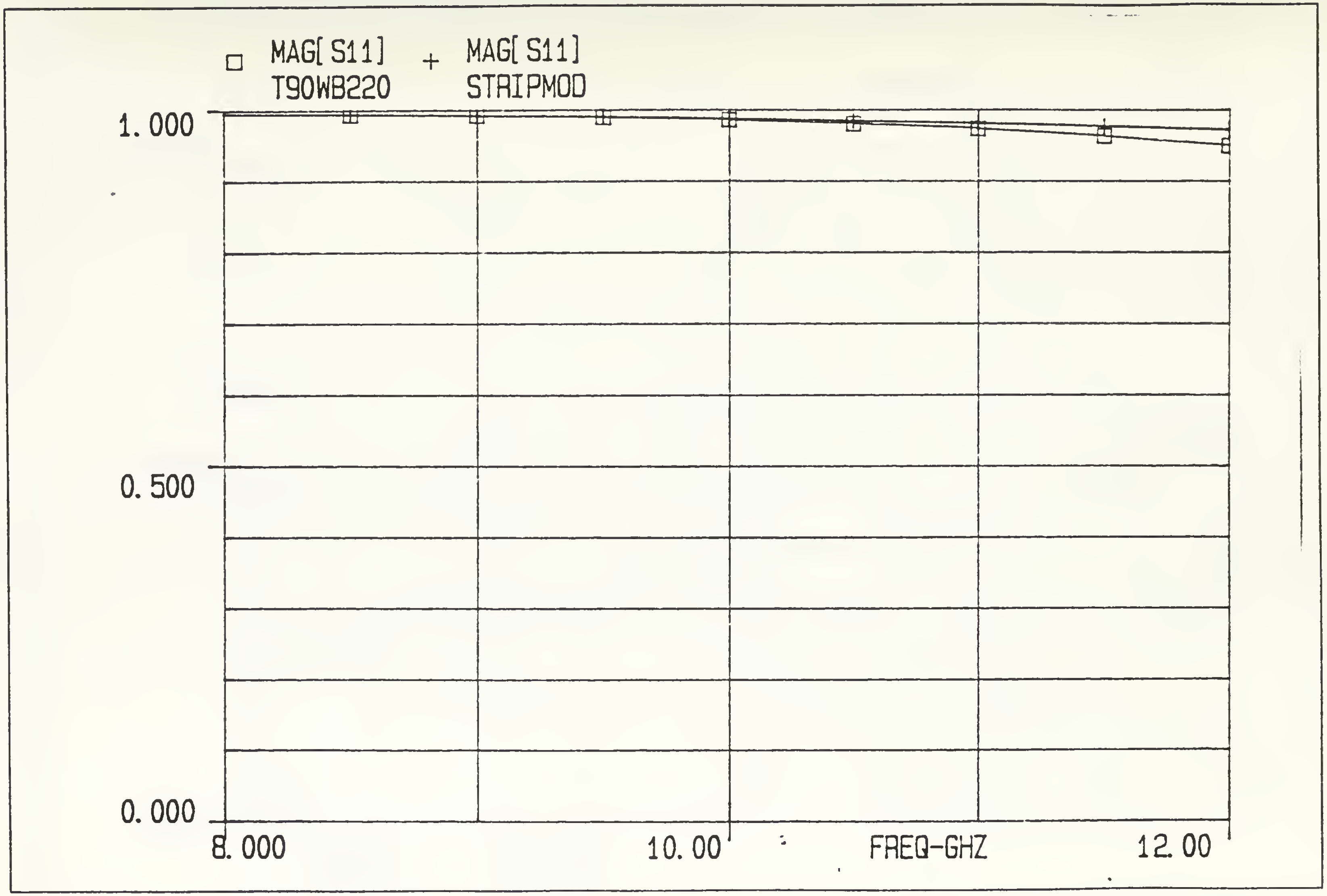


Figure 58. Computed and predicted values of $|S_{11}|$ vs. frequency for a T = 200 mils inductive strip centered in WR(90) fin-line, W/b = 0.2, $E_{r2} = 1$. Model inductance L = 3.06 nH.

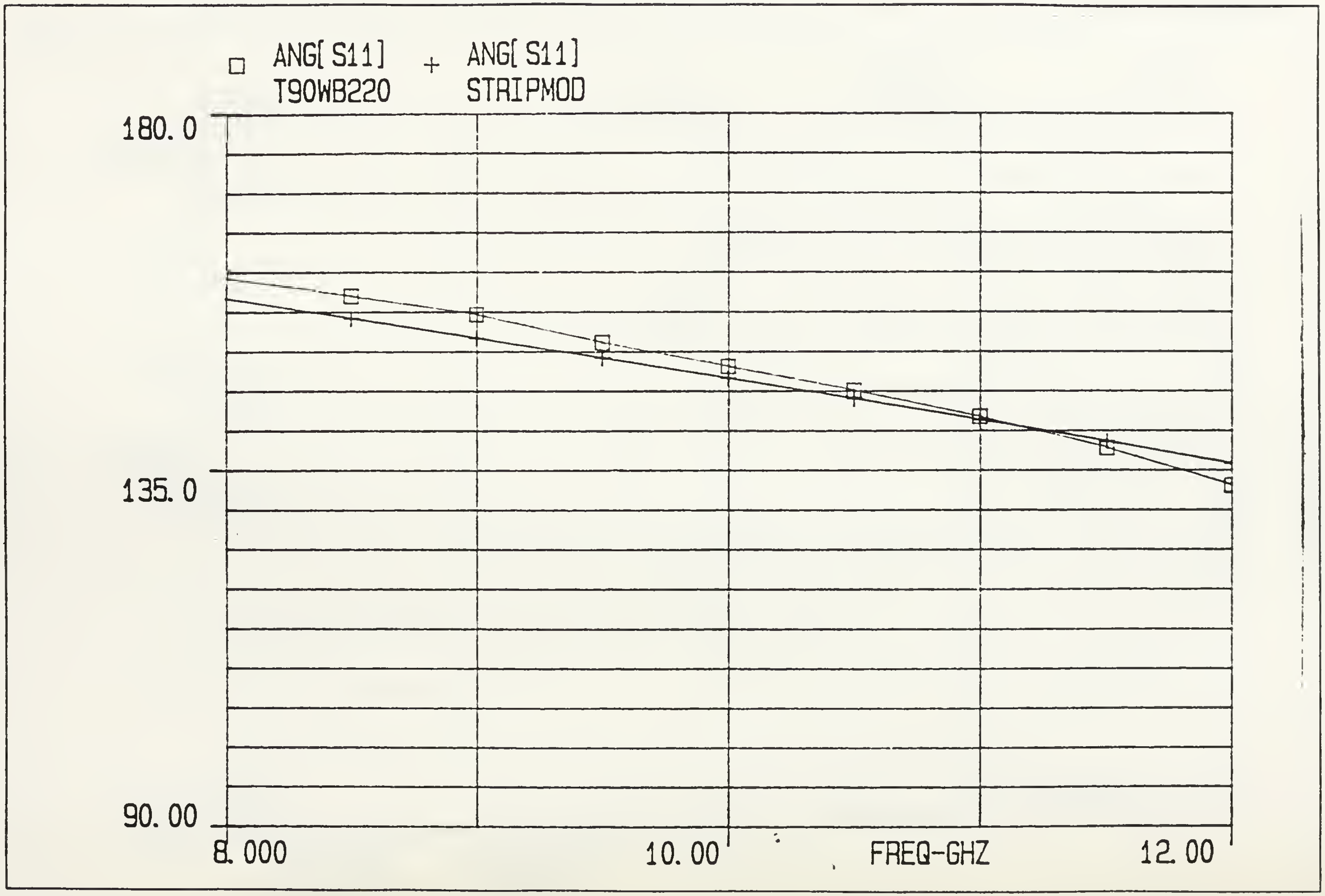


Figure 59. Computed and predicted values of θ_{11} vs. frequency for a T = 200 mils inductive strip centered in WR(90) finline, W/b = 0.2, E_{r2} = 1. Model inductance L = 3.06 nH.

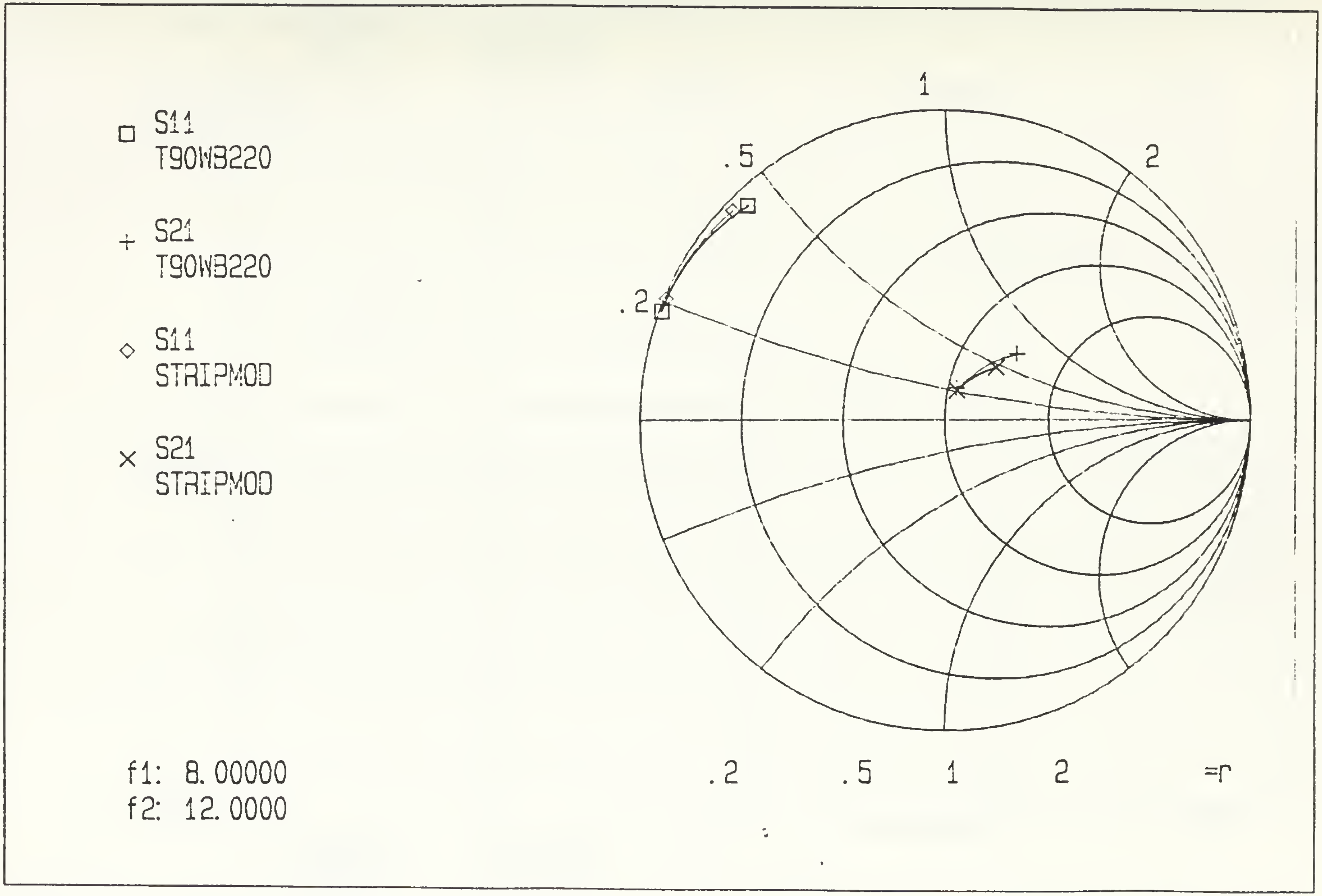


Figure 60. Smith chart plot of computed and predicted values of S_{11} and S21 for a T = 200 mils inductive strip centered in WR(90) fin-line, W/b = 0.2, E_{r2} = 1. Model inductance L = 3.06 nH.

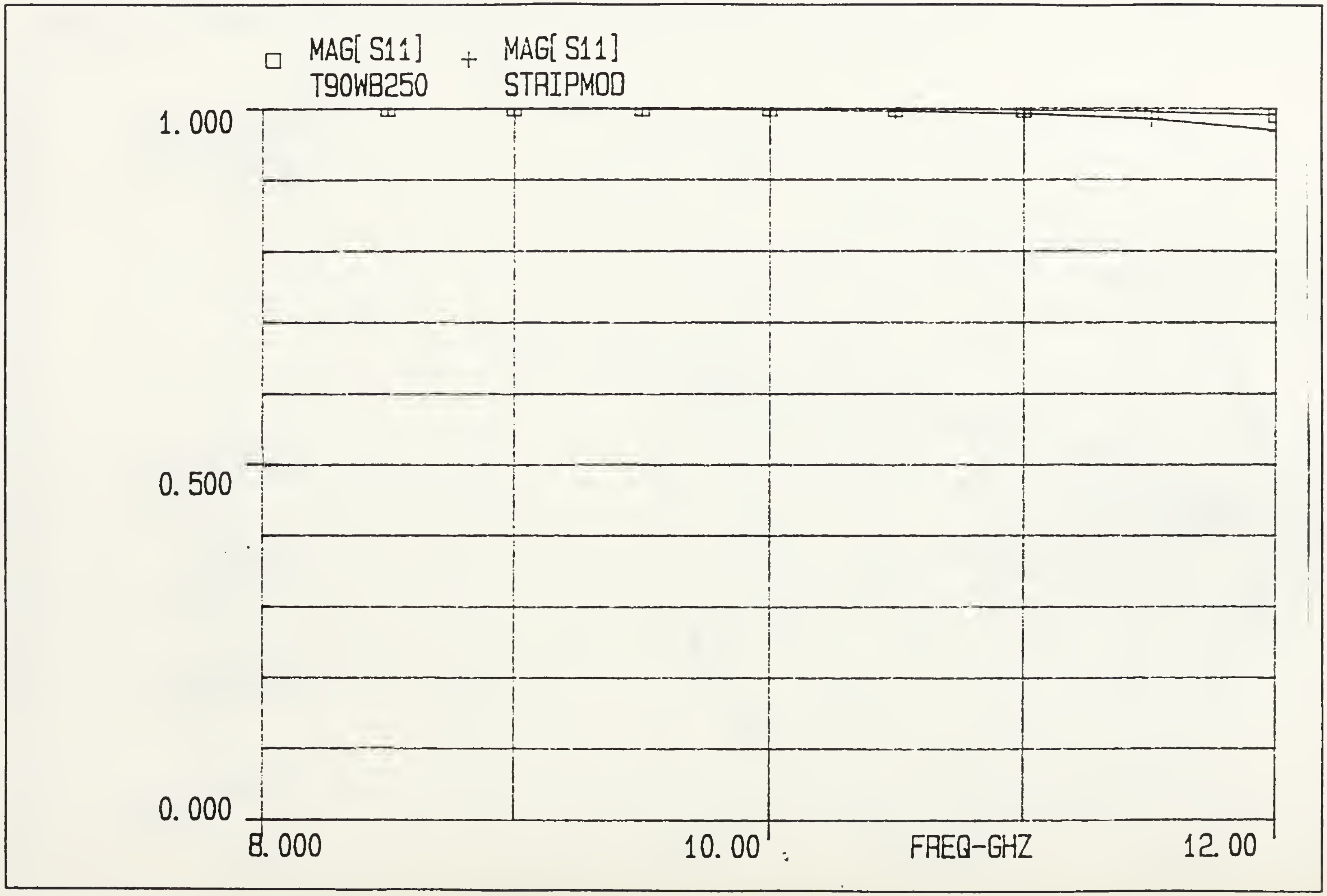


Figure 61. Computed and predicted values of $|S_{11}|$ vs. frequency for a T = 500 mils inductive strip centered in WR(90) fin-line, W/b = 0.2, E_{r2} = 1. Model inductance L = 2.70 nH.

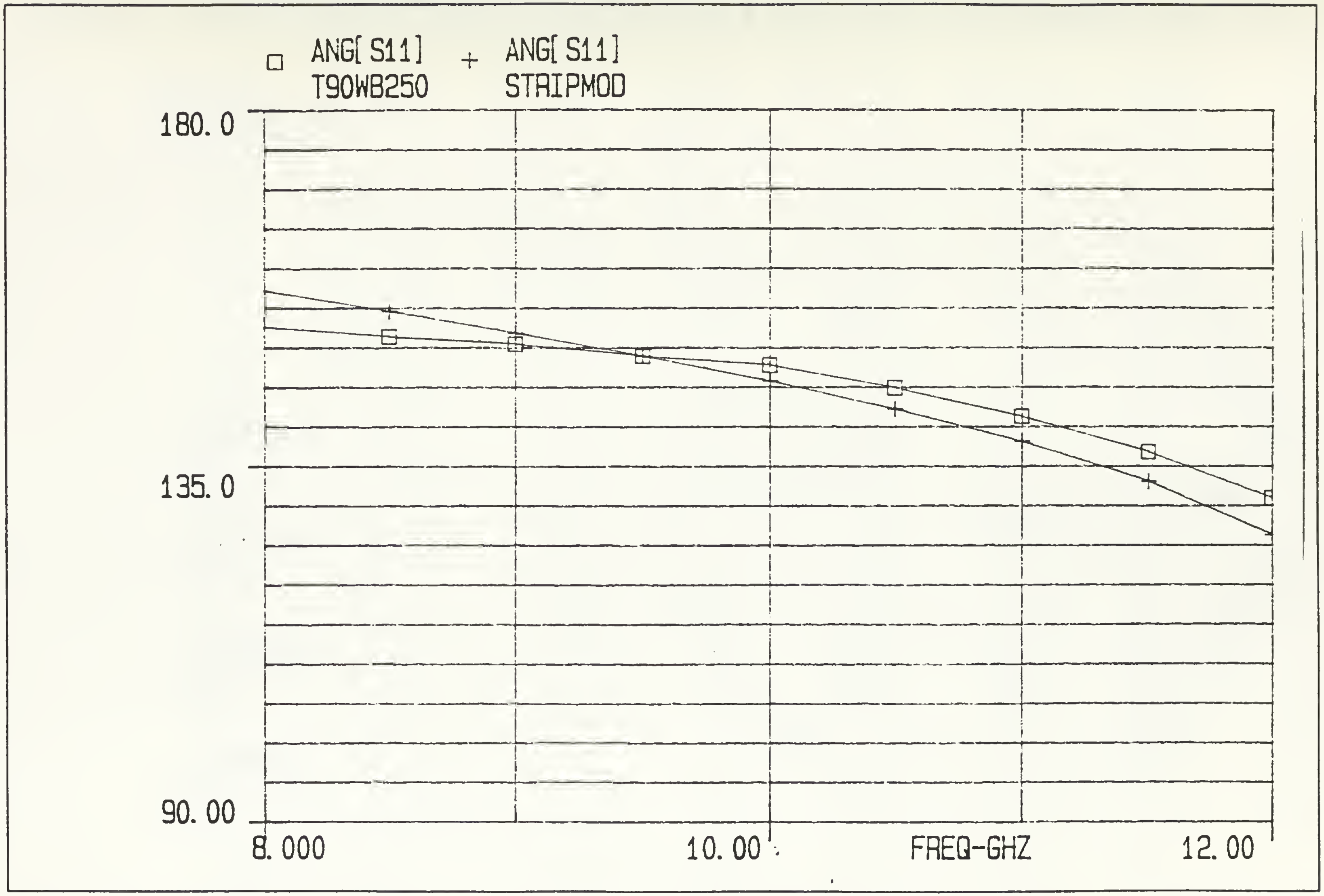


Figure 62. Computed and predicted values of θ_{11} vs. frequency for a T = 500 mils inductive strip centered in WR(90) finline, W/b = 0.2, E_{r2} = 1. Model inductance L = 2.70 nH.

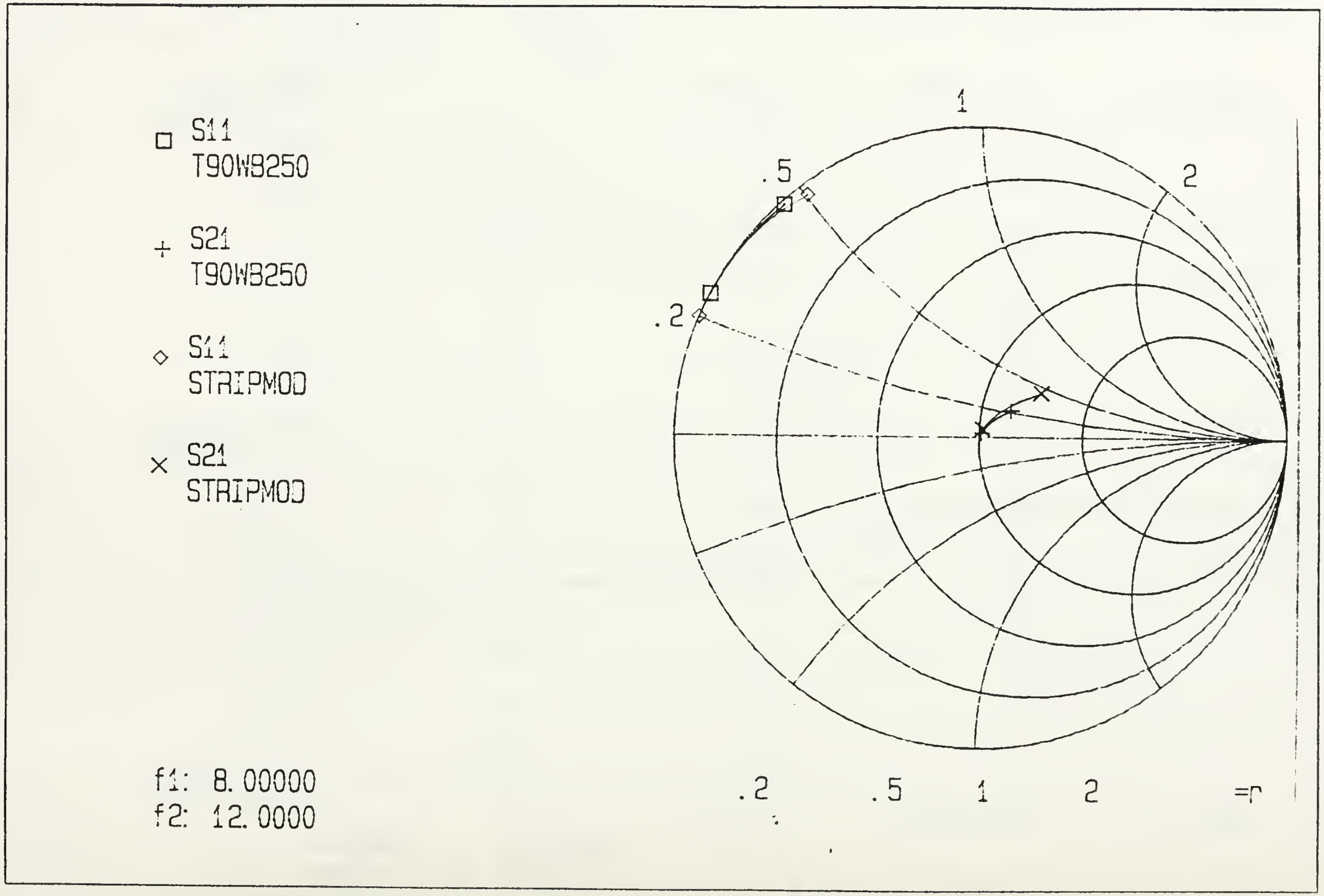


Figure 63. Smith chart plot of Computed and predicted values of S_{11} and S21 for a T = 500 mils inductive strip centered in WR(90) fin-line, W/b = 0.2, E_{r2} = 1. Model inductance L = 2.70 nH.

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